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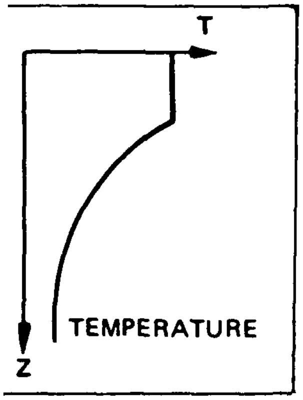

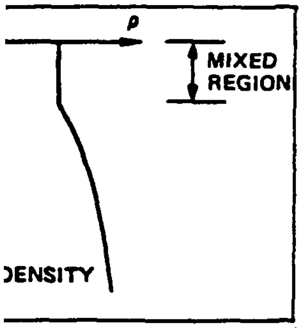

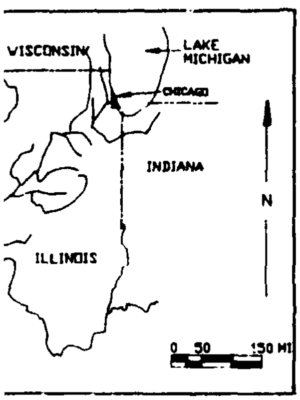

HYDRAULICS LABORATORY

TECHNICAL REPORT HL-91-17

McCOOK RESERVOIR WATER QUALITY MODEL

Numerical Model Investigation

by

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13. ABSTRACT *(Maximum 200 words)*

The McCook Reservoir is a planned flood storage reservoir for the city of Chicago. Since the storm water which would fill the reservoir could contain domestic sewage, concerns were expressed with the development of anoxic conditions in the reservoir and the subsequent development of hydrogen sulfide gas. A one-dimensional numerical model was modified to predict the development of anoxic conditions by the uptake of dissolved oxygen from biochemical oxygen demand (BOD). A routine was added to simulate the effects of thermal destratification using a pneumatic diffuser system. Simulations conducted with the model included water years with high rainfall, low rainfall, and average rainfall conditions. Two period of record storm events were also simulated. Results of the simulations indicated the model was most sensitive to inflow concentration of BOD. Destratification alone had little effect on prevention of anaerobic conditions in the reservoir. A pneumatic aeration system was designed using oxygenation requirements predicted by the numerical model.

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PREFACE

The numerical model investigation of the McCook Reservoir, Illinois, reported herein, was conducted by the US Army Engineer Waterways Experiment Station (WES) at the request of the US Army Engineer District, Chicago.

The investigation was conducted during the period June 1989 to March 1991 in the Hydraulics Laboratory (HL) and Environmental Laboratory (EL), WES, under the direction of Mr. Frank A. Herrmann, Jr., Chief, HL; Dr. John Harrison, Chief, EL; Mr. Richard A. Sager, Assistant Chief, HL; Dr. John W. Keeley, Assistant Chief, EL; Messrs. Glenn A. Pickering, Chief, Hydraulic Structures Division (HSD), HL; and Donald L. Robey, Chief, Ecosystem Research and Simulation Division (ERSD), EL; and under the direct supervision of Dr. Jeffery P. Holland, Chief, Reservoir Water Quality Branch (RWQB), HSD, and Dr. Mark S. Dortch, Chief, Water Quality Modeling Group (WQMG), ERSD. This report was prepared by Dr. Richard E. Price, RWQB, and Ms. Dottie Tillman, WQMG, and edited by Mrs. Marsha C. Gay, Information Technology Laboratory, WES.

Commander and Director of WES during preparation of this report was COL Larry B. Fulton, EN. Dr. Robert W. Whalin was the Technical Director.

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MCCOOK RESERVOIR WATER QUALITY MODEL

Numerical Model Investigation

PART I: INTRODUCTION

Background on McCook Reservoir

1. The Chicagoland Underflow Project (CUP) is a flood-control project for the city of Chicago (Figure 1). This project consists of a series of tunnels and drop shafts that connect to existing storm sewers. The metropolitan sewage system and storm drains are connected; therefore, during storm events, sewage can back up into residences. To alleviate this condition, large-diameter tunnels were bored through rock approximately 200 ft (61 m) below the ground surface. The storm sewers are connected to the tunnels at intervals with drop shafts. During storm events, overflow from the storm drains empties into these drop shafts and then into the tunnels. When the CUP is complete, the tunnels will empty into existing stone quarries which will serve as storage reservoirs prior to the water being pumped to wastewater treatment facilities.

2. The proposed McCook Reservoir (Figure 2), which is an active investigation of the US Army Engineer District, Chicago, is currently a stone quarry designated to be a storage reservoir. As part of the CUP, the Mainstream and Des Plaines River tunnels would be extended to the quarry to drain this portion of the tunnel system and provide approximately 32,000 acre-feet (39.5 m^3) of storage. Since the reservoir walls will be nearly vertical, the reservoir will have a nearly constant surface area of 218 acres (88 hectares) at all elevations. At full capacity, the water depth will be approximately 150 ft (47.7 m). Uncontrolled inflow to the reservoir during a storm event may approach 60,000 cfs (1,700 m^3/sec) and can fill the reservoir in 48 hours or less. After the storm has passed, the inflow structure, presently to be located near the southeast corner of the reservoir, will be closed and the tunnel will be dewatered. Because a portion of the tunnel is required for conveyance of water to the wastewater treatment facility, dewatering of the reservoir will not begin until the tunnel is dewatered, a process requiring approximately 3 days to complete. The reservoir will be dewatered at a

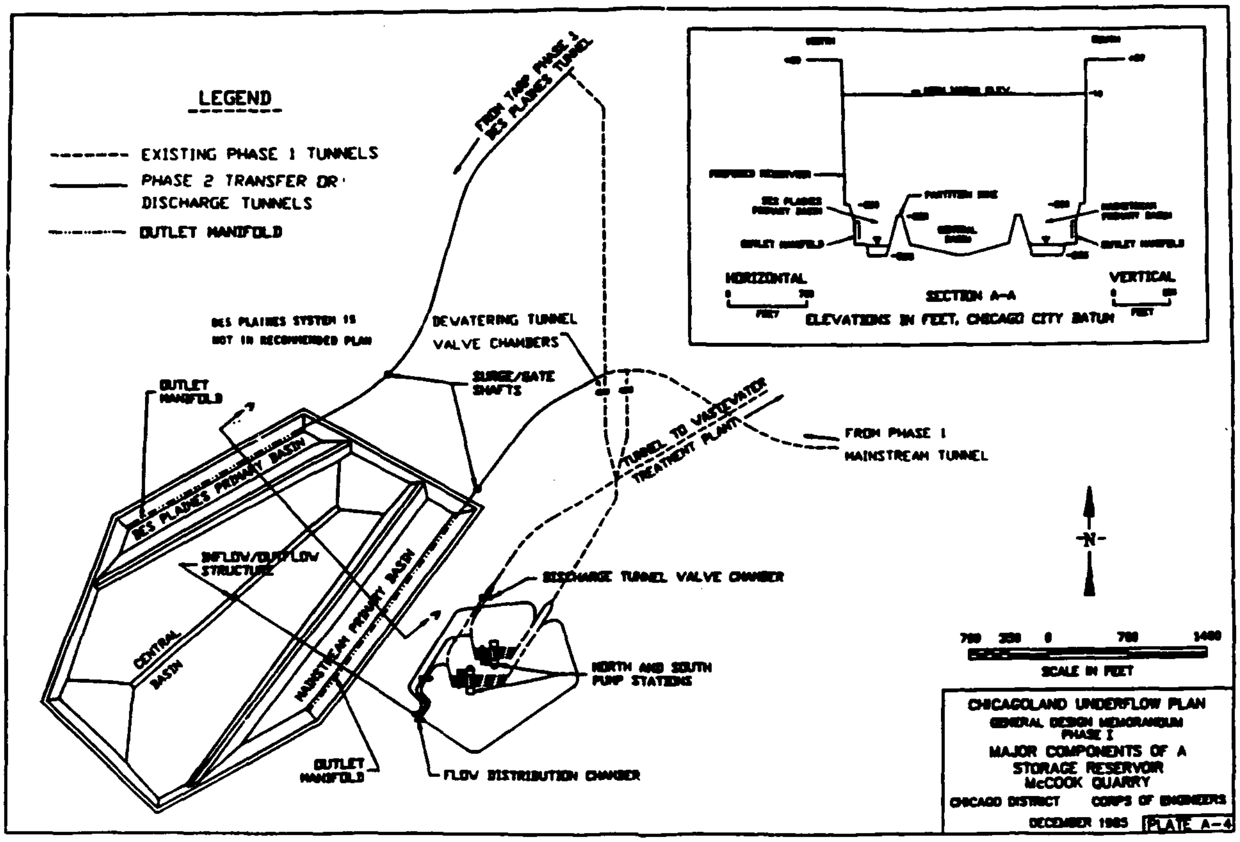

Figure 1. Schematic of McCook Reservoir

constant rate of 385 cfs (10.9 m^3/sec) through an outflow structure to be located near the center of the reservoir.

3. The dewatering of the reservoir at maximum pool will take approximately 40 days. Due to the presence of raw sewage and urban runoff in the inflow, the biochemical oxygen demand (BOD) will be high (the Chicago District* estimated approximately 30 mg/ℓ) as compared to normal run-off (which is normally below 5 mg/ℓ). Therefore, the dissolved oxygen (DO) will be depleted rapidly, and in the absence of reaeration, anaerobic processes will begin. These processes will generate hydrogen sulfide gas, which is noxious and potentially health-threatening. The water quality concerns of this project are primarily prevention of escape of these gases to the atmosphere. The Chicago District is evaluating two approaches to prevent the escape of these gases: the maintenance of aerobic conditions in the surface layer to prevent

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* Personal Communication, 12 March 1990, with Mr. Steve Garbaciak, Chicago District.

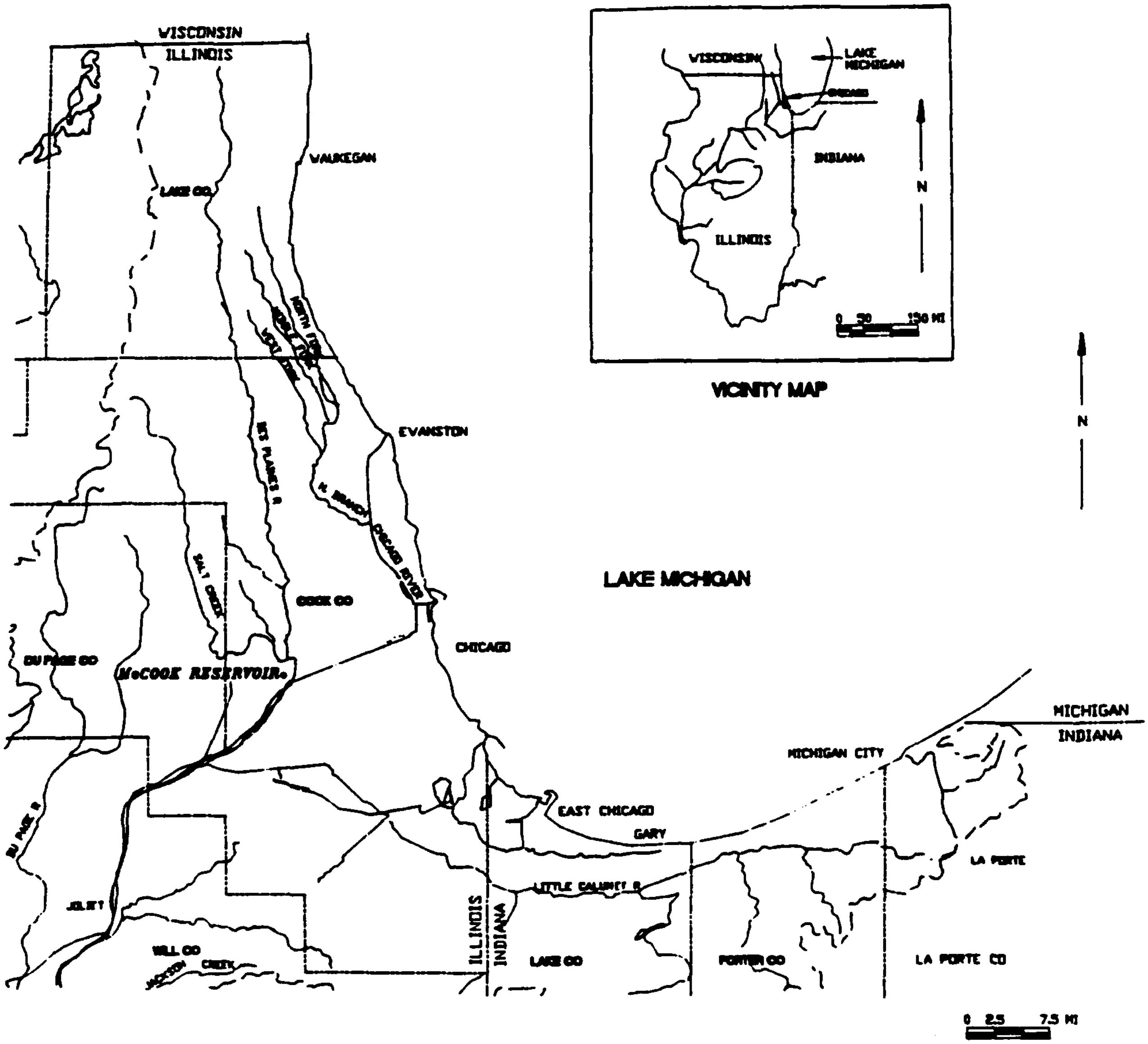


Figure 2. Vicinity and location maps (from Fletcher 1991)

escape of hydrogen sulfide or maintenance of aerobic conditions in the entire reservoir to prevent formation of hydrogen sulfide. Although Shelef, Ronen, and Kremer (1977) reported that a concentration of 0.5 mg/ℓ DO on the surface of wastewater treatment ponds was sufficient to prevent emission of odors, a DO concentration of 2.0 mg/ℓ or greater was used to define aerobic conditions for this investigation. This higher concentration was selected since reduction processes have not been reported to occur at DO concentrations above 2.0 mg/ℓ.

Background on Hydrogen Sulfide

4. The production of hydrogen sulfide by bacterial sulfate reduction has been investigated mostly in lake and marine sediments (Maeda and Kawai 1988; Jorgensen 1977). Investigations of the impacts of hydrogen sulfide within the water column of lakes have been investigated to a lesser extent. Effler et al. (1988) have investigated the impacts of high concentrations of hydrogen sulfide on DO in the epilimnion of Onondaga Lake, New York. This hypereutrophic lake develops strong thermal stratification with the hypolimnion becoming anoxic in early June of each year. Production of hydrogen sulfide in the hypolimnion begins and concentrations build up until overturn in the fall. With overturn, mixing of hypolimnetic water with epilimnetic water results in lakewide depletion of DO. Since hydrogen sulfide is highly soluble in water with a half-life of only 5 to 10 min in the presence of oxygen (Jorgensen, Kuenen, and Cohen 1979), overturn results in the rapid depletion of surface DO with concentrations dropping to 1 mg/ℓ.

5. Brinkmann and De M. Santos (1974) investigated the emission of hydrogen sulfide from Amazonian floodplain lakes during the passage of weather fronts. During periods when the lakes were stratified, hydrogen sulfide built up in the hypolimnion. Upon passage of a front, the surface water cooled and overturn occurred. Severe oxygen depletion then occurred over the entire water column and hydrogen sulfide was detectable throughout the water column. On several occasions, the hydrogen sulfide odor was detected with frontal passage. The authors also indicated that as the surface elevation of the floodplain lakes declined with falling river stages, the emission of hydrogen sulfide became more probable. This was due to increased production of hydrogen sulfide in the hypolimnion, increased mixing with lower stages, and lower pressure on the hypolimnion with lower stages.

Study Objectives and Scope

6. The Chicago District proposed two approaches to the prevention of the release of gases from the reservoir. The first involves reaeration of the entire reservoir to maintain aerobic conditions by mixing the reservoir to ensure uniform conditions. The second involves aerating the surface layers to maintain an aerobic layer similar to the facultative pond approach used in

wastewater treatment facilities. Hydrogen sulfide would be produced in the anaerobic bottom layers but would be oxidized before reaching the water surface. If the stability of the vertical profile is disturbed, as might occur with passage of a weather front or inflow of additional storm water, the release of hydrogen sulfide could occur. Therefore, this approach relies on stratification to assist in maintaining the stability of the surface layer.

7. The evaluation of both these approaches requires detailed modeling to simulate stratification and DO under anticipated operating conditions. Since the reservoir DO will be consumed primarily by the BOD, the modeling approach must be responsive to BOD demands. Historically, numerical models at the US Army Engineer Waterways Experiment Station have simulated DO based primarily on surface aeration, respiration, and consumption by sediment processes. Demand on DO from organic matter was not simulated. Therefore, the objectives of this investigation were to (a) provide a literature review of hydrogen sulfide control methods, (b) modify the one-dimensional model CE-QUAL-R1 to model BOD as a major sink of DO, (c) conduct simulations of various inflow and outflow conditions for both design approaches to assess their abilities to meet a prescribed DO objective, (d) determine the required oxygen delivery rates for DO maintenance under various operating conditions, and (e) develop general design guidance for the aeration or destratification system. The Chicago District also requested modifications to the model to include a pneumatic destratification routine, simulation of additional operational scenarios, analysis of the sensitivity of predicted DO to various input parameters, and additional diffuser design information. These objectives are addressed in the following sections.

PART II: REVIEW OF HYDROGEN SULFIDE CONTROL TECHNIQUES

Overview of Alternatives

8. The review of techniques that may be applicable to the control of hydrogen sulfide at McCook Reservoir was the first objective of this investigation. Although this review centered on aeration techniques, the literature on emission of hydrogen sulfide gas indicated several methods to control hydrogen sulfide in wastewater facilities. These techniques range from methods to prevent the formation of hydrogen sulfide to masking the odor with chemicals once it has been released to the atmosphere.

9. In cold climates, such as in Canada, design criteria for wastewater facilities to prevent emission of hydrogen sulfide consist of limiting the organic loading to the pond. A facultative approach (which is the maintenance of aerobic conditions near the surface with anaerobic conditions on the bottom) is taken and functions as designed, provided that loading is maintained within design limits (Oleszkiewicz and Sparling 1987). Anaerobic lagoon design (a facultative approach) for treating food processing wastes is based on small surface-to-volume ratios to minimize surface reaeration (Miner 1978). One major problem with this design approach is emission of odors with excessive loading of the lagoon. Since control of the BOD loading to the McCook Reservoir is not possible, this approach is not feasible.

10. Several authors reported modifications of the pH of the influent to prevent emission of hydrogen sulfide. In this design approach, the pH of the pond is maintained above 8.0 to convert most sulfides to the bisulfide ion form (Polprasert and Chatsanguthai 1988). Poduska and Anderson (1980) designed a diffuser system for distribution of sodium nitrate to an industrial wastewater lagoon to raise the pH above 9.0 and successfully control hydrogen sulfide emission. Although aeration alternatives were investigated, chemical addition was more cost effective since it was a waste byproduct available on site.

11. Aeration is one method used to prevent anaerobic production of hydrogen sulfide for odor control in waste treatment ponds. Gilliland (1970) devised a simple aeration system consisting of pumping surface water from a lagoon through an irrigation system equipped with spray nozzles to spray the water over the lagoon surface. This facultative approach controlled odor

emission from a poultry manure storage lagoon as long as the intake for the pump was located in an aerated portion of the lagoon. On several occasions, the intake withdrew water from the anaerobic layer and odors were reported from the lagoon. Ginnivan and Eason (1983) reported on an odor control method for anaerobic lagoons (facultative approach) that treat piggery wastes. They indicated that intermittent shallow aeration is just as effective in preventing odor emission as is continuous aeration. Both forms of aeration were significantly more effective than no aeration. They also indicated that odor control was possible in a facultative anaerobic lagoon with a shallow aerated surface layer. This information indicates that aeration in facultative anaerobic lagoons prevents hydrogen sulfide gas from escaping; however, operational control is difficult to maintain, especially for weakly stratified systems subject to high inflows as may occur with the McCook Reservoir.

12. Essentially, as discussed, there were three types of alternatives for the control of hydrogen sulfide emissions: (a) limit the organic loading to the treatment facility, e.g., the McCook Reservoir, (b) use chemicals to raise the pH of the treatment facility to inhibit hydrogen sulfide emission, and (c) use aeration systems that either prevent the occurrence of anaerobic conditions or prevent the escape of hydrogen sulfide with an aerated zone at the surface of the treatment facility. The first two are not feasible alternatives for the operation of the McCook Reservoir. However, the aeration technique (c) appears to be the most applicable. The remainder of this report focuses on the design character and implementation of this type of hydrogen sulfide control system.

Aeration System Design Considerations

13. According to Busch (1983), wastewater aeration design must consider the major factors that influence oxygen transfer: temperature, suspended solids concentration, intensity of aeration (air flow rate per diffuser), mixing, surfactants or other constituents that may influence surface exchange, and surges in organic loading. Since McCook Reservoir will be receiving dilute sewage, surfactants and surges in organic loading should not have as strong an influence as temperature, intensity of aeration, and mixing. In addition, the primary design consideration is maintenance of aerobic conditions and not assimilation of BOD loadings as is the case in most waste

treatment facilities. The suspended solids concentration should have a minimal impact on aeration design, but further analysis of suspended solids loads to the reservoir may be needed. The water temperature in the McCook Reservoir will be dependent primarily on inflow temperature and surface heat exchange. Although surface aeration may reduce surface temperatures due to evaporative cooling, lowering of the temperature to increase oxygen transfer is not feasible. Therefore, intensity of aeration and mixing are the primary factors to consider in the aeration design.

14. Intensity of aeration refers to the volume of air delivered per diffuser orifice. The air flow rate per orifice is based on the oxygen transfer efficiency for the diffuser. Although two basic types of diffusers are used, distinction between the two, relative to bubble size, is not clear (Water Pollution Control Federation and American Society of Civil Engineers 1988). Fine bubble diffusers generate small bubbles through a porous diffuser, and coarse bubble diffusers produce large bubbles through ports or slots. Either air, oxygen-enriched air, or oxygen may be used with either type of diffuser. Efficiency of oxygen transfer is generally better with fine bubble diffusers than coarse bubble diffusers. The depth of the diffuser also affects oxygen transfer efficiency with higher efficiencies achieved at greater depths. This is offset by the energy required for the compressed air system to overcome the increased pressure at greater depth and therefore usually results in a relatively constant system aeration efficiency regardless of depth.

15. Mixing refers to the hydraulic action delivered by an aeration system to ensure uniform conditions within a basin. The objective of mixing is to circulate each parcel of water through the influence of the aeration device before the DO is depleted. In relation to the McCook Reservoir aeration system, sufficient energy for mixing must be available and distributed such that each parcel of water comes in contact with the system before the DO in that parcel drops below 2.0 mg/ℓ. This mixing may be achieved with pneumatic diffuser systems installed on the reservoir bottom or mechanical pumps located on the reservoir surface. For reservoir pneumatic destratification systems, the air flow rate per orifice is determined on the basis of diffuser depth and degree of stratification in the reservoir (Davis 1980). Although oxygen transfer from the bubble plume occurs, the mixing action and the amount of water entrained by the bubble plume are the important considerations.

Reservoir mixing may also be achieved using surface mechanical pumps. Design criteria for destratification systems using pumps are available (Price 1989); however, aeration with this approach is entirely through reaeration (oxygenation) at the water surface. With high DO depletion rates as may be observed in the McCook Reservoir, reaeration through surface exchange may not be sufficient to prevent production of hydrogen sulfide. Therefore, surface aerators may be required in addition to surface pumps.

16. There is a wealth of literature on aeration systems used for wastewater treatment. Although the design of these systems is usually based on a BOD loading and water flow rate, the aeration (reaction) basin is usually maintained at a constant volume. With the design of an aeration system for McCook Reservoir, the changing volume (and depth) will also have to be considered in the system design. However, a combination of reservoir destratification/aeration technology with typical wastewater treatment design procedures may yield a system design for McCook Reservoir.

PART III: McCOOK RESERVOIR WATER QUALITY MODEL

17. A major objective of this investigation was to modify the water quality model CE-QUAL-R1 to predict DO based on BOD. The modifications of the model to accomplish this task as well as other modifications for McCook Reservoir are discussed in this part.

CE-QUAL-R1 Model

18. The CE-QUAL-R1 model (Environmental Laboratory 1982) is a one-dimensional model of water quality that describes the vertical distribution of thermal energy and biological and chemical variables in a reservoir with time. The biological and chemical components of the model (hereafter referred to as the McCook model) were simplified to simulate variables that create the greatest demand on DO. A subroutine to model BOD was added to the McCook model since this variable is the major sink of DO in the McCook reservoir.

19. The reservoir in the McCook model is conceptualized as a vertical series of horizontal layers in which thermal energy and mass are uniformly distributed. Horizontal layer thickness is variable and dependent on the balance of inflowing and outflowing waters. Variable layer thicknesses permit accurate mass balancing and reduce numerical dispersion during periods of large inflow and outflow.

20. Inflowing waters are distributed vertically based on density so that simulations of surface flows, interflows, and underflows are possible. Water density is dependent on temperature and total dissolved and suspended solid concentrations. Outflowing waters are withdrawn from layers based on density stratification using the selective withdrawal algorithms of Bohan and Grace (1973).

21. The heat budget includes the components of shortwave and longwave radiation, back radiation, reflected solar and atmospheric radiation, evaporative loss, conductive heat transfer, and gain or loss through inflow and outflow. Vertical transport of thermal energy and mass is achieved through entrainment and turbulent diffusion. Entrainment determines the depth of the upper mixed layer and the onset of stratification. It is calculated from the turbulent kinetic energy influx generated by wind shear and convective mixing using an integral energy approach (Johnson and Ford 1981). Turbulent

diffusion is a two-way transport process incorporating a turbulent or eddy diffusion coefficient that depends on wind speed, magnitude of inflows and outflows, and density stratification.

22. Biological and chemical variables included in the McCook model were DO, BOD, sulfide, and sulfate. Forces that directly affect the concentrations of these constituents are temperature, irradiation, wind speed, inflow and outflow rates, and inflowing and outflowing constituents. The physical distribution of mass is dependent upon the diffusive and convective processes described in the preceding paragraph and on photosynthesis, respiration, excretion, decomposition, and DO exchange at the air-water interface.

BOD Conversion

23. BOD was modeled using first-order reaction kinetics and was expressed as:

$$\frac{dL_t}{dt} = KL_t \tag{1}$$

where

L_t = amount of the first-stage BOD remaining in the water at time t, mg/ℓ

t = time

K = oxidation rate (Metcalf and Eddy, Inc., 1979), ℓ/day

After integration this equation becomes

$$L_t = L_o e^{-Kt} \tag{2}$$

where

L_o = BOD when $t = 0$ (i.e., initial conditions), mg/ℓ

24. The BOD data for this model were input as the standard 5-day BOD. These values were converted to ultimate BOD values using the equation:

$$L_u = \frac{L_5}{(1.0 - e^{-5K_1})} \tag{3}$$

where

L_u = ultimate BOD

L_5 = 5-day BOD

K_1 = the "bottle rate" constant (Thomann and Mueller 1987)

A typical value of K_1 for polluted water and wastewater is 0.23 per day (Metcalf and Eddy, Inc., 1979). Thomann and Mueller (1987) recommend that for deep water bodies this value be used for the first K_1 approximation. Since McCook is considered a deep reservoir and will be filled with a mixture of stormwater and wastewater, this value was used in the ultimate BOD equation.

25. Temperature effects on the oxidation rate K were taken into account using the equation

$$K_1^T = K_1^{20}\,\theta^{(T-20)} \tag{4}$$

where

K_1^T = reaction constant at temperature T

K_1^{20} = reaction constant at 20° C

θ = 1.047

The value used for the temperature correction constant θ was the suggested default value from Brown and Barnwell (1987).

Modifications to the Model

26. A number of additional modifications were made to the McCook version of the CE-QUAL-R1 model to improve DO predictions. The first modification was the inclusion of a different wind-induced surface reaeration formulation from O'Connor (1983) instead of the original Kanwisher (1963) formulation. O'Connor's formulation, tested using the DeGray 1979 input data set (Wlosinski and Collins 1985), resulted in improved surface DO concentrations. The O'Connor formulation for wind reaeration is written as:

$$K_L = \frac{U_*}{\dfrac{\Gamma\,Sc^{2/3}}{\kappa^{1/3}\sqrt{\rho_r}} + \sqrt{\dfrac{\kappa\,z_{o*}\,Sc}{\rho_r}}} \tag{5}$$

where

K_L = mass transfer coefficient caused by wind stress, cm/sec

U_* = shear velocity, cm/sec, calculated by $U_* = CdW^{1/2}$ where Cd = drag coefficient and W = wind speed, cm/sec

Γ = viscous sublayer thickness, dimensionless

Sc = Schmidt number, dimensionless

κ - Von Karman's constant, dimensionless

ρ_r - air-water density ratio

z_{o+} - dimensionless roughness length

The parameters Γ and z_{o+} are expressed by:

$$\Gamma = \Gamma_o \quad \text{when } U_* < U_{*c} \tag{6}$$

$$\Gamma = \Gamma_o \frac{U_*}{U_{*c}} e^{1-U_*/U_{*c}} \quad \text{when } U_* \geq U_{*c} \tag{7}$$

$$z_{o+} = \frac{1}{\frac{\nu}{z_e U_*} + \lambda_1 e^{-U_*/U_{*t}}} \tag{8}$$

where

Γ_o - dimensionless viscous sublayer thickness for smooth flow

U_{*c} - critical shear velocity of wind at which rapid erosion of the viscous sublayer occurs, cm/sec

ν - kinematic viscosity, cm^2/sec

z_e - equilibrium roughness length, cm

λ_1 - reciprocal roughness Reynolds number

U_{*t} - shear velocity that characterizes transition from smooth to rough flow, cm/sec

Values used for these parameters in the wind reaeration formulation are from O'Connor (1983) and are shown in the following tabulation:

Parameter	Value	Parameter	Value
U_{*c}, cm/sec	9.2	S_c	500
z_e, cm	0.25	U_{*t}, cm/sec	10
K, ℓ/day	0.4	Γ_o	4
ν, cm^2/sec	0.15	λ_1	2.5
		ρ_r	0.0012

27. The second modification to the model was to calculate the DO saturation concentration using the Mortimer (1981) equation instead of the original equation in CE-QUAL-R1. DO saturation concentration was necessary in evaluating wind reaeration. The Mortimer equation is the standard for DO saturation (American Public Health Association, American Water Works

Association, and Water Pollution Control Federation 1985) and is expressed as:

$$C_s = \exp\{7.7117 - 1.31403[\ln (T + 45.93)]\} * Pa \qquad (9)$$

where

C_s = DO saturation concentration at temperature T, mg/ℓ

T = water temperature of the surface, °C

Pa = correction term for altitude

Pa is calculated as:

$$Pa = \left(1 - \frac{H}{44.3}\right)^{5.25} \qquad (10)$$

where

H = altitude of the reservoir, km.

28. The final modification to the model to improve DO predictions was to reduce the turbulent kinetic energy generated by the wind. The sheltering effects of the terrain surrounding a reservoir can have a significant effect on the amount of wind reaeration generated. To modify the amount of wind reaeration actually taking place, the surface area was reduced by the fraction (sheltering coefficient, SHELCF) of the reservoir being influenced by the sheltering effects (Environmental Laboratory 1982). *Of particular importance* in the McCook Reservoir is the sheltering effect due to the water surface being well below the normal ground surface. The sheltering coefficient in the model accounts for the impacts local topography has on surface reaeration from wind. McCook Reservoir is approximately 4,200 ft (1280 m) in the longest fetch, but if prevailing wind is from the northwest, then it is 2,450 ft (747 m). At the full pool, the surface will be 50 ft (15 m) below ground level. Using the procedure recommended by Environmental Laboratory (1982), the wind will reattach to the surface approximately 403 ft (121 m) from the reservoir boundary. The effective fetch is 3 or 4 times this reattachment length; therefore, sheltering may not be significant. For all simulations except those used for sensitivity analysis, the sheltering coefficient was set to 1.0 to maximize reaeration by the wind. A value of 0.0 could be used to prevent entrainment due to wind mixing.

29. To predict the amount of oxygen required to maintain aerobic conditions in the reservoir (2.0 mg/ℓ), a routine was added to the oxygen subroutine. This addition consisted of an input parameter for the minimum oxygen

concentration to be simulated in each layer. This minimum oxygen concentration would allow the model to simulate DO but not allow the DO in each layer to drop below the minimum value. For example, when the minimum oxygen parameter was set to 0.0, the routine was inactive and DO was not added to any layer. When the parameter was set to 2.0 mg/ℓ, the routine would artificially add DO to maintain 2.0 mg/ℓ in each layer. The mass of DO required to keep each layer at 2.0 mg/ℓ was summed for all layers at each computational interval. This total mass could then be used to determine oxygenation system capacity for the reservoir under various operational scenarios.

Pneumatic Destratification Routine

30. Reservoir destratification is a technique that may be used to maintain a fully mixed environment as proposed for the McCook Reservoir. This may be accomplished using surface pumps to effect fully mixed environments with hydraulic jets similar to mixing in wastewater treatment facilities. However, the constant change in surface elevation of the McCook Reservoir would create design and operational problems for surface pumps. Pneumatic diffusers may also be used to effect destratification, as is done in many water supply reservoirs. This could be accomplished through installation of diffusers on the reservoir bottom that would create mixing through bubble plumes as they rise to the surface. Design of destratification systems involves evaluation of the desired degree of mixing with the amount of energy required to achieve that degree of mixing.

31. To evaluate the effects of destratification on the McCook Reservoir and the subsequent amount of oxygen required to maintain aerobic conditions, a numerical destratification routine was added to the model. In this destratification routine, the reservoir is divided into a near field model and a far field model. The near field model simulates the bubble plume and the entrained flow associated with it. The far field model simulates the effects of the flow away from the plume and the flow toward the plume, as well as the effects of mixing on the rest of the reservoir. To initiate the destratification routine in the model, air flow rate must be set to some positive number. Additional input required are the diffuser depth and number of diffusers. Detailed description of the theoretical aspects of the model are found in Zic and Stefan (1990).

Graphical Routines

32. The McCook model simulates temperature, DO, BOD, sulfate, and hydrogen sulfide for each computation reservoir layer. Therefore, profiles of these parameters are predicted for each time-step and are available in printed output form. To examine temperature, DO, and BOD profiles over time, a contour plotting routine was written using DISSPLA routines. Profiles are output for each time-step to a file during execution of CE-QUAL-R1. Upon completion of the simulation, the plot code is then executed, which generates a contour plot with elevation and time for temperature, DO, and BOD. When the minimum oxygen routine is turned on in the model, the amount of oxygen required to maintain the input minimum is plotted.

PART IV: RESULTS OF SIMULATIONS

Operational Scenarios

33. Potential McCook operational scenarios were developed in conjunction with the Chicago District. Hydrologic inflow events for 2-, 10-, 50-, and 100-year flood events were available from the Chicago District for simulation. Two flood events (October 1954 and July 1957) were also provided by the Chicago District. In consultation with the Chicago District, the 10-year flood and the two period-of-record flood events were selected for simulation. The inflow hydrographs for these events are shown in Figure 3.

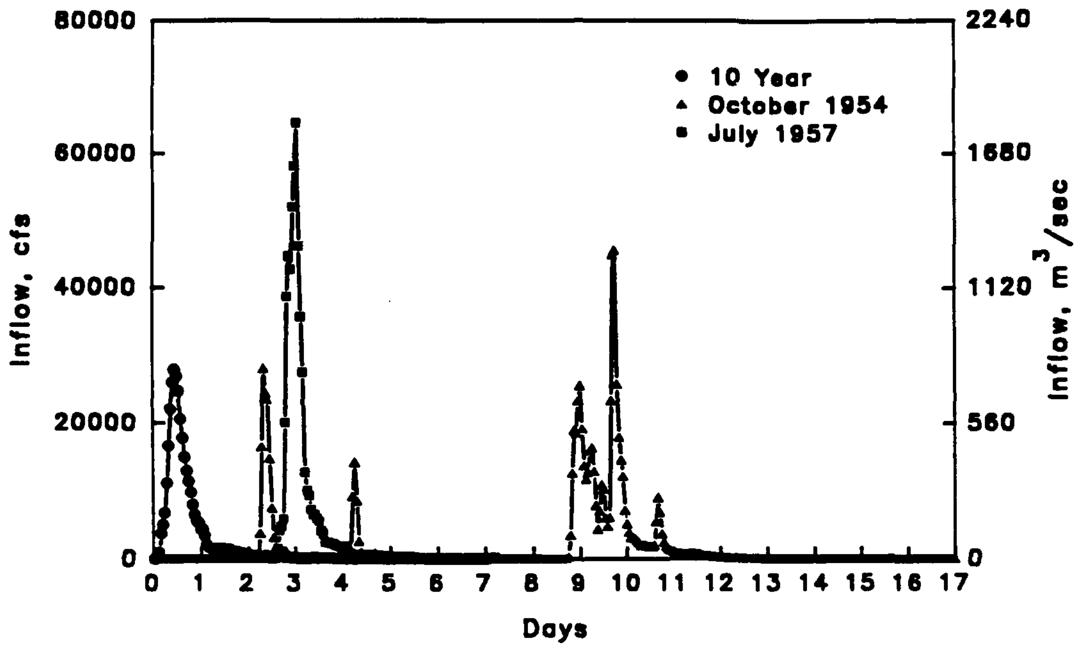


Figure 3. Inflow hydrographs for 10-year, 1954, and 1957 flood events for McCook Reservoir

34. To simulate the impacts of various meteorological conditions, weather data for 1949, 1982, and 1962 were used to simulate average, wet, and dry meteorological conditions, respectively. Thus, the impacts of extreme conditions may be compared to those of average conditions. The 10-year flood event would require approximately 2 days to fill the reservoir, 3 days to evacuate the tunnel, and another 40 days to dewater the reservoir, for a total simulation time of 45 days. To examine the effects of season on the reservoir, three simulations were conducted for each year, the first beginning 30 April and ending 13 June to represent spring conditions, the second

beginning 14 June and ending 28 July to represent summer conditions, and the third beginning September 15 and ending October 30 to represent fall conditions. The two period-of-record floods, which would have filled the reservoir, were simulated in the season as they occurred using actual inflow volumes and meteorological conditions. The October 1954 flood began 1 October with inflow partially filling the reservoir. Prior to complete filling on 13 October, some inflow was pumped out. The July 1957 flood was similar to the 10-year flood in that the reservoir filled in the first 2 days and was held stable for 3 days prior to initiating the drawdown. Since the reservoir does not currently exist, inflow water quality data do not exist. In consultation with the Chicago District, inflow water quality for all scenarios was set at 30 mg/ℓ BOD (5 day) with a DO of 6 mg/ℓ and temperature of 20° C, which are the anticipated water quality conditions for most inflow events.

35. Simulations were conducted with these operational scenarios to examine the effects of meteorological conditions on reservoir thermal stratification and DO. These simulations were used to determine the degree of thermal stratification that would develop in the reservoir for evaluation of the facultative pond and fully mixed approaches in managing hydrogen sulfide.

36. The 1949 (average year) spring simulation (Figure 4) indicated little thermal or DO stratification would develop. As indicated by the BOD plot, the BOD exerted its demand on the DO with the initial filling but declined rapidly. When the minimum oxygen routine was initiated, the model predicted a peak oxygen demand of approximately 320 tons/day (290 metric tons/day) for the full pool. As the BOD was assimilated and the volume of the pool was reduced during drawdown, the oxygen input rate dropped significantly. Simulation of summer conditions for 1949 (Figure 5) indicated significant thermal stratification developed, beginning with the drawdown of the pool. A concurrent DO stratification was also predicted, possibly due to convective circulation as well as wind-driven currents. The BOD exhibited a pattern similar to that of the spring simulation; however, the BOD was assimilated more quickly in the summer probably due to warmer conditions. The predicted maximum oxygen input rate to maintain 2 mg/ℓ in the reservoir was similar to that for the spring simulation. The fall simulation (Figure 6) of thermal conditions was similar to that of the spring, in that little stratification developed. This resulted in little DO stratification but a BOD pattern similar to previous simulations. The amount of oxygen required to maintain 2 mg/ℓ

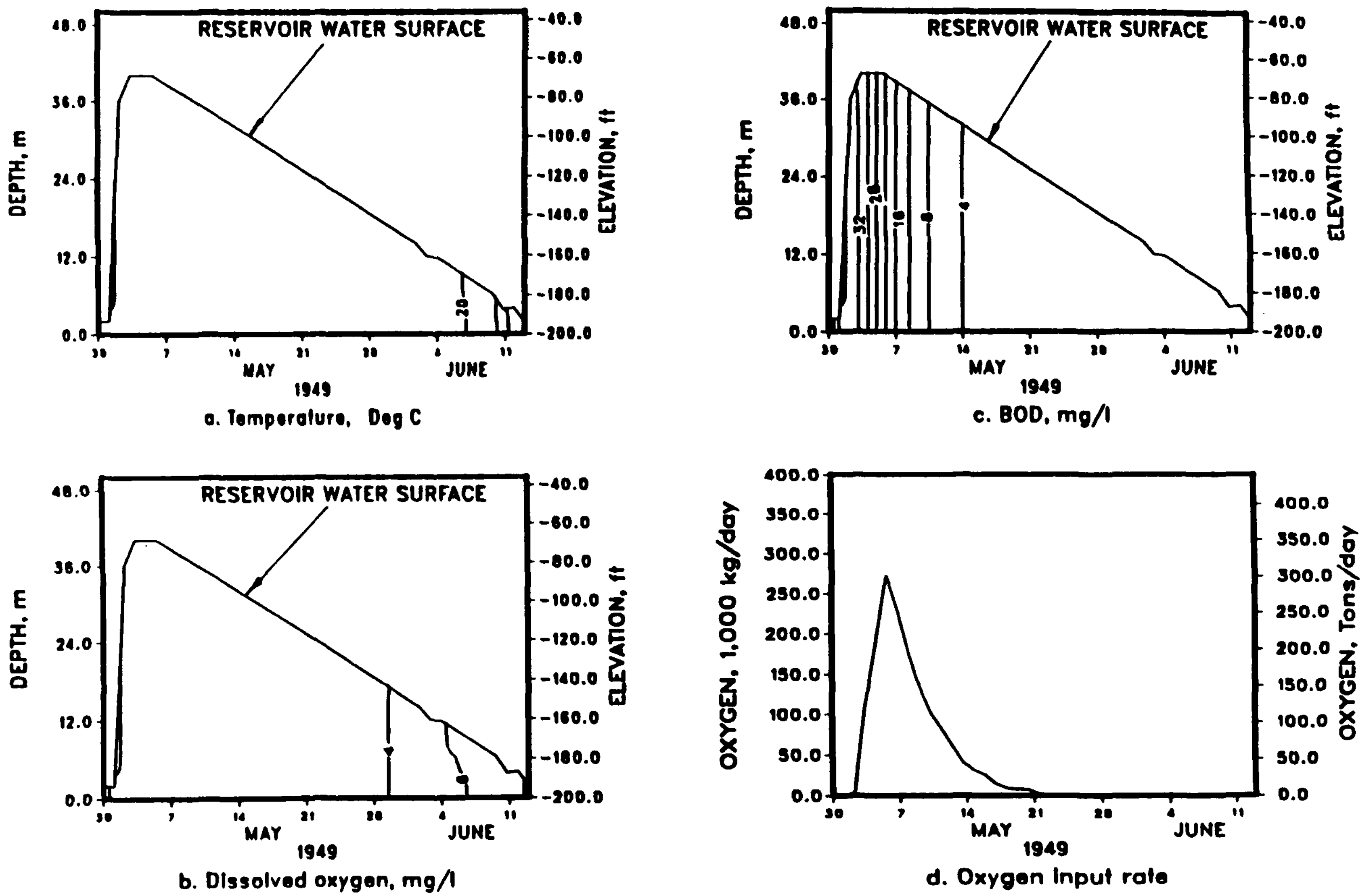


Figure 4. Temperature, DO, and BOD isoplots and required oxygenation rate for spring 1949 meteorological conditions

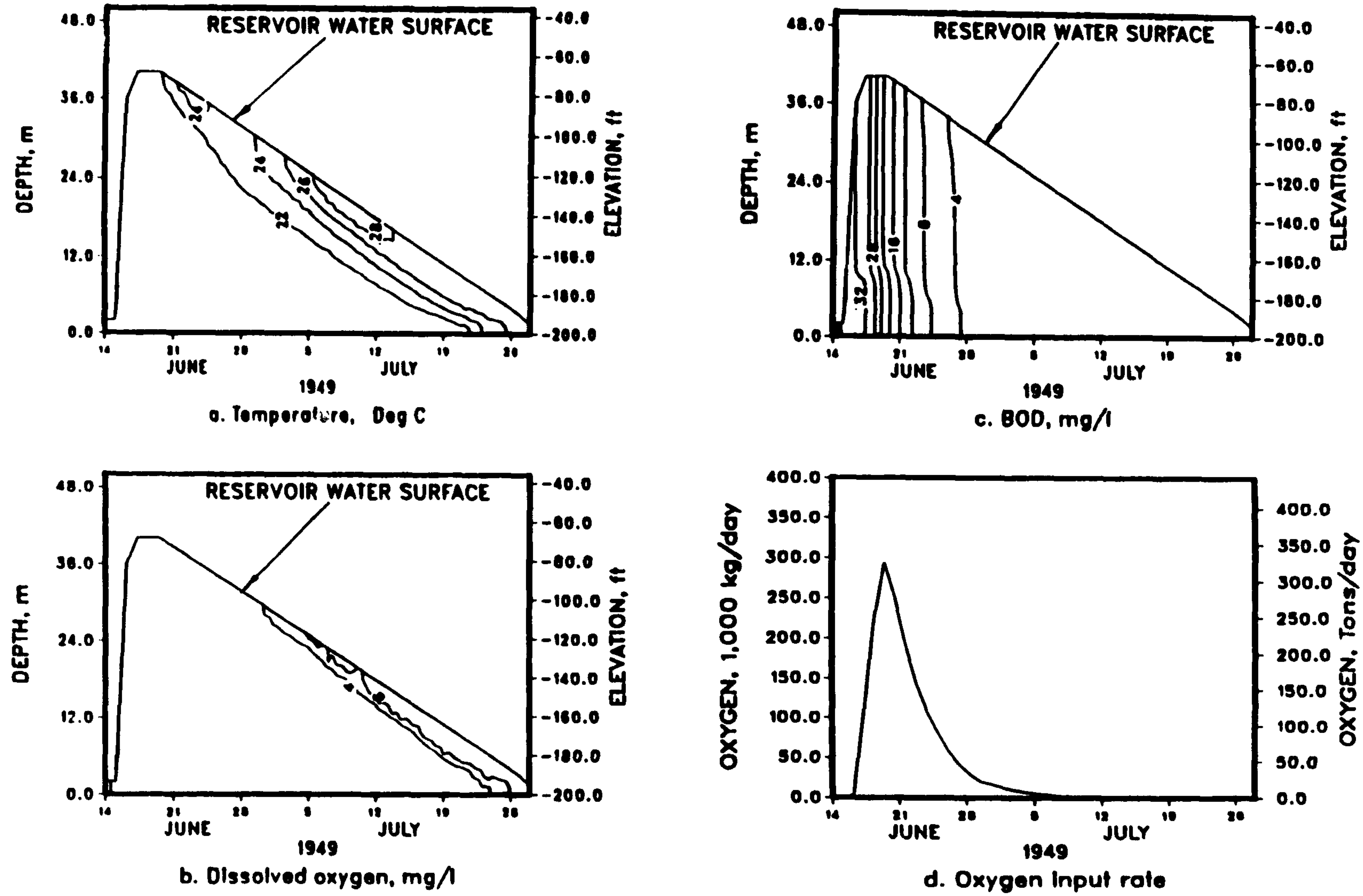


Figure 5. Temperature, DO, and BOD isoplots and required oxygenation rate for summer 1949 meteorological conditions

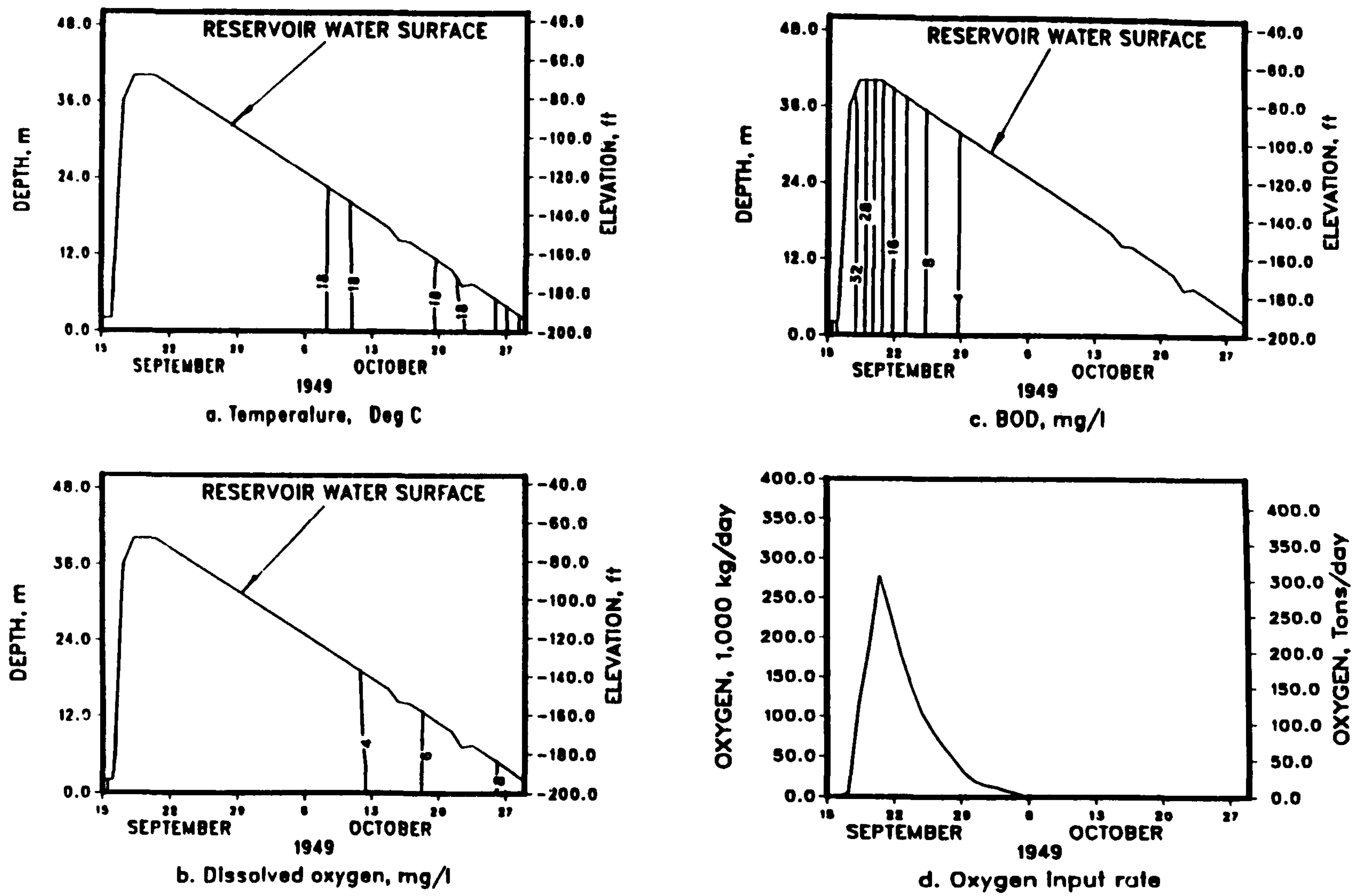


Figure 6. Temperature, DO, and BOD isoplots and required oxygenation rate for fall 1949 meteorological conditions

was also similar at a maximum rate of approximately 300 tons/day.

37. The 1982 (wet year) simulation of spring conditions (Figure 7) resulted in little thermal stratification but indicated the development of some DO stratification. Simulation of BOD was similar to 1949 predictions, as was the required predicted oxygen input volume. The summer simulation for 1982 (Figure 8) indicated development of thermal stratification with the thermocline deep in the reservoir and development of some DO stratification. The BOD profiles appeared similar to those of the spring simulation and the predicted oxygen input rate was approximately 280 tons/day (254 metric tons/day). The fall simulation (Figure 9) was similar to spring conditions; however, little, if any, stratification developed. BOD and required oxygen input rate were similar to spring and summer simulations.

38. The 1962 (dry year) simulation of spring conditions (Figure 10) was similar to the 1982 spring simulation with little thermal stratification developing in the reservoir. Some DO stratification was evident and BOD profiles were similar to those of the 1982 simulation, as was the predicted oxygen input rate. The 1962 simulation of summer conditions (Figure 11) indicated weak thermal stratification with concurrent DO stratification. BOD profiles as well as predicted oxygen input rate were similar to those of previous simulations. Simulation of fall conditions for 1962 (Figure 12) indicated some thermal stratification with DO stratification developing in mid-October. BOD and oxygen input rate were similar to those of previous simulations.

39. The simulation of the 1957 flood event (Figure 13) covered a period in late summer from July to August, but did not indicate the development of thermal stratification or DO stratification. BOD profiles were similar to those of previous simulations with the predicted maximum oxygen input rate near 350 tons/day (318 metric tons/day).

40. The simulation of the 1954 flood event (Figure 14) covered a period in the fall from October to late November. The inflow hydrograph was different from previous simulations in that the reservoir received inflow to partially fill the pool with a delay of several days before complete filling. This maintained mixed conditions for a longer initial period as indicated by the lack of temperature contours. Thermal or DO stratification did not develop and probably would not since most reservoirs in this part of the country would be isothermal at this time of the year. BOD did not reach

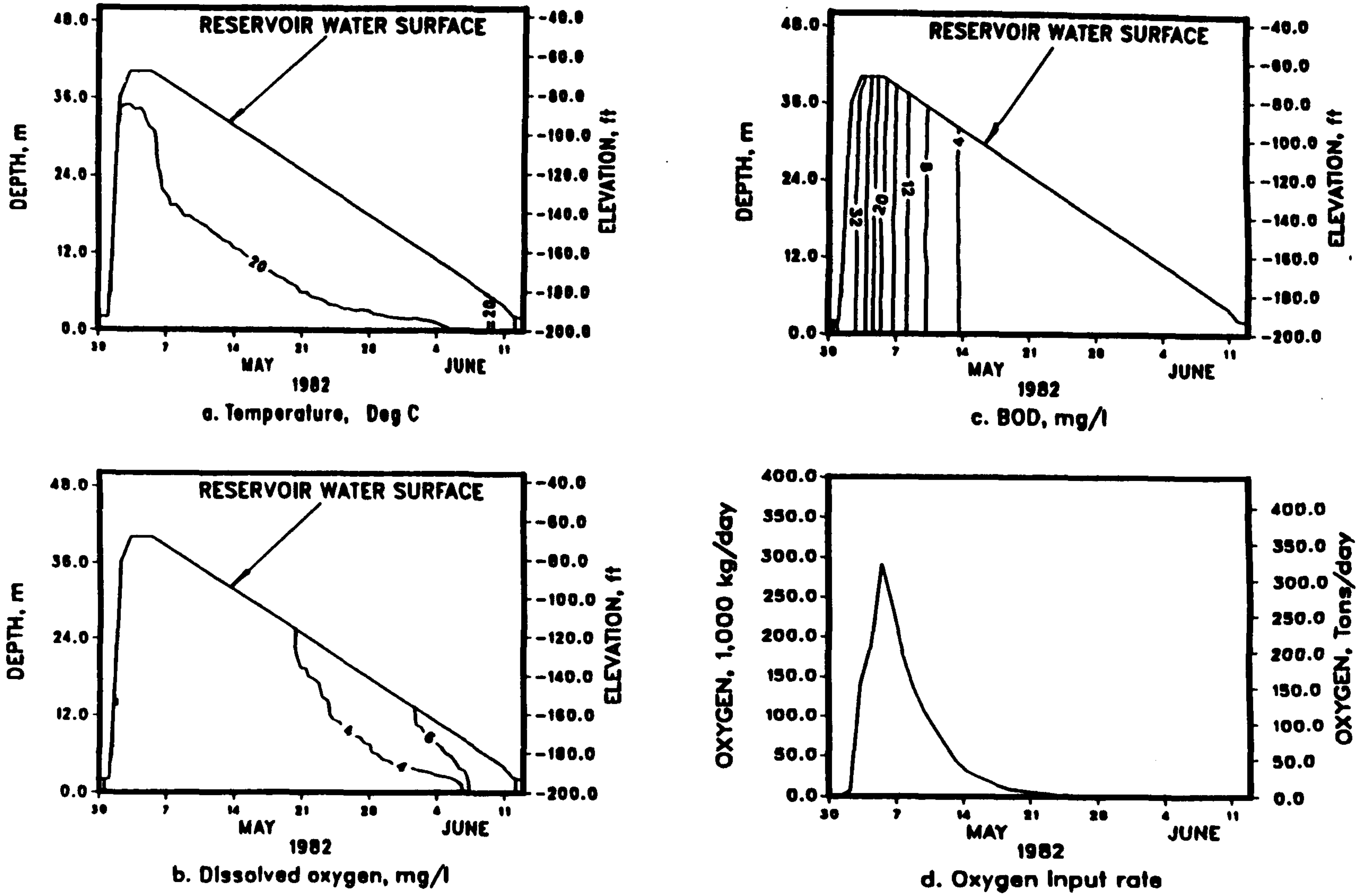


Figure 7. Temperature, DO, and BOD isoplots and required oxygenation rate for spring 1982 meteorological conditions

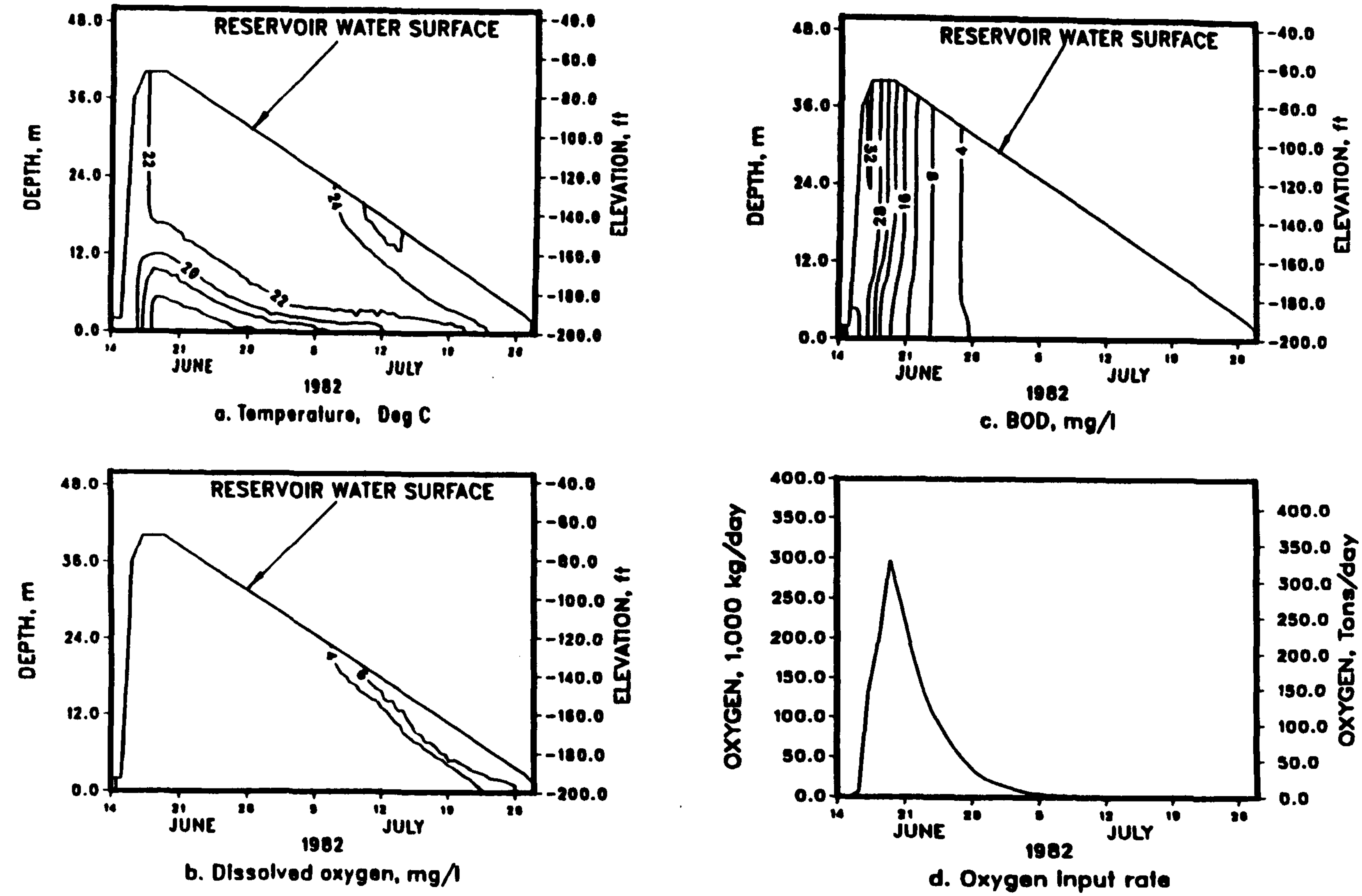


Figure 8. Temperature, DO, and BOD isoplots and required oxygenation rate for summer 1982 meteorological conditions

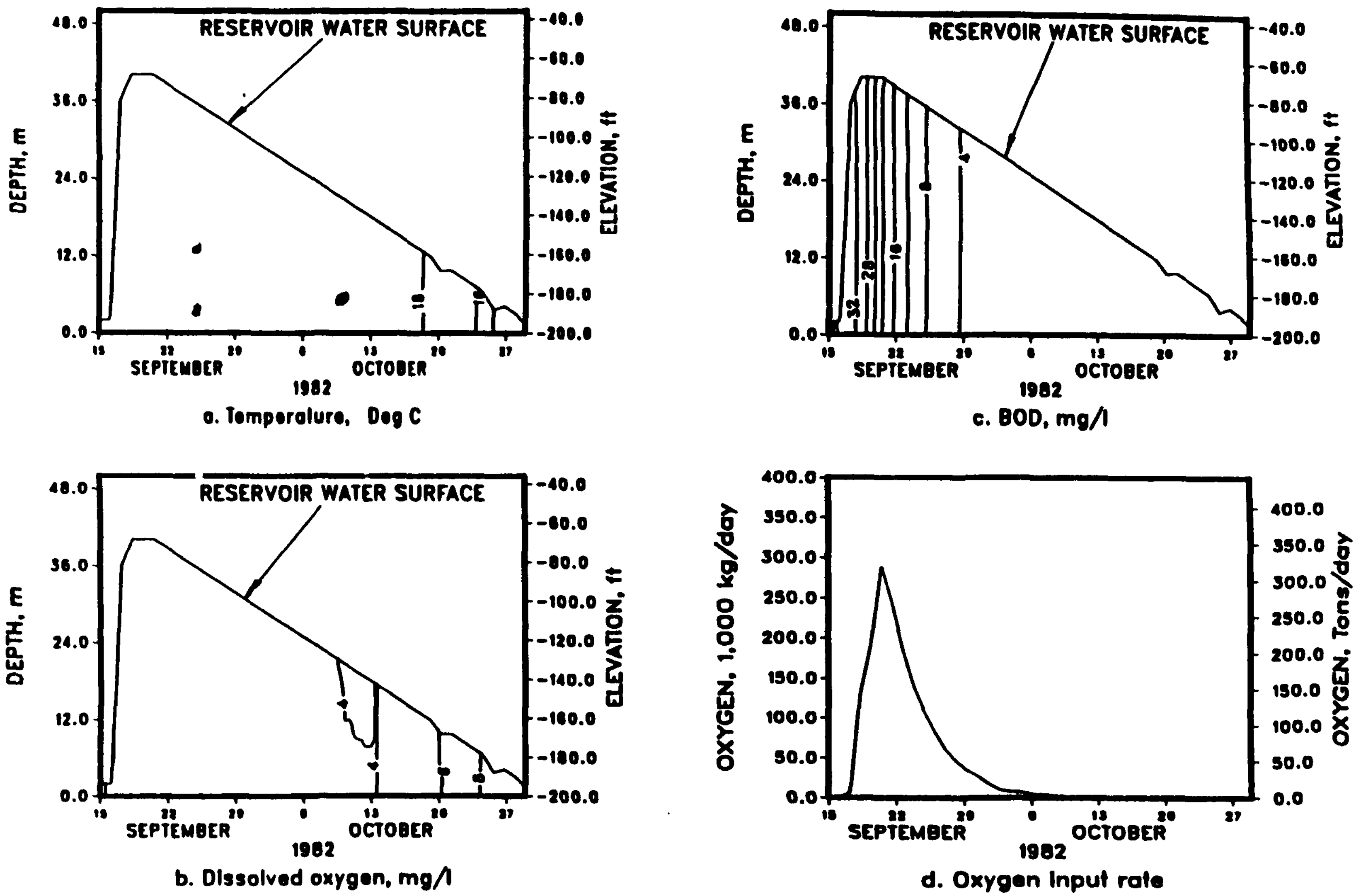


Figure 9. Temperature, DO, and BOD isoplots and required oxygenation rate for fall 1982 meteorological conditions

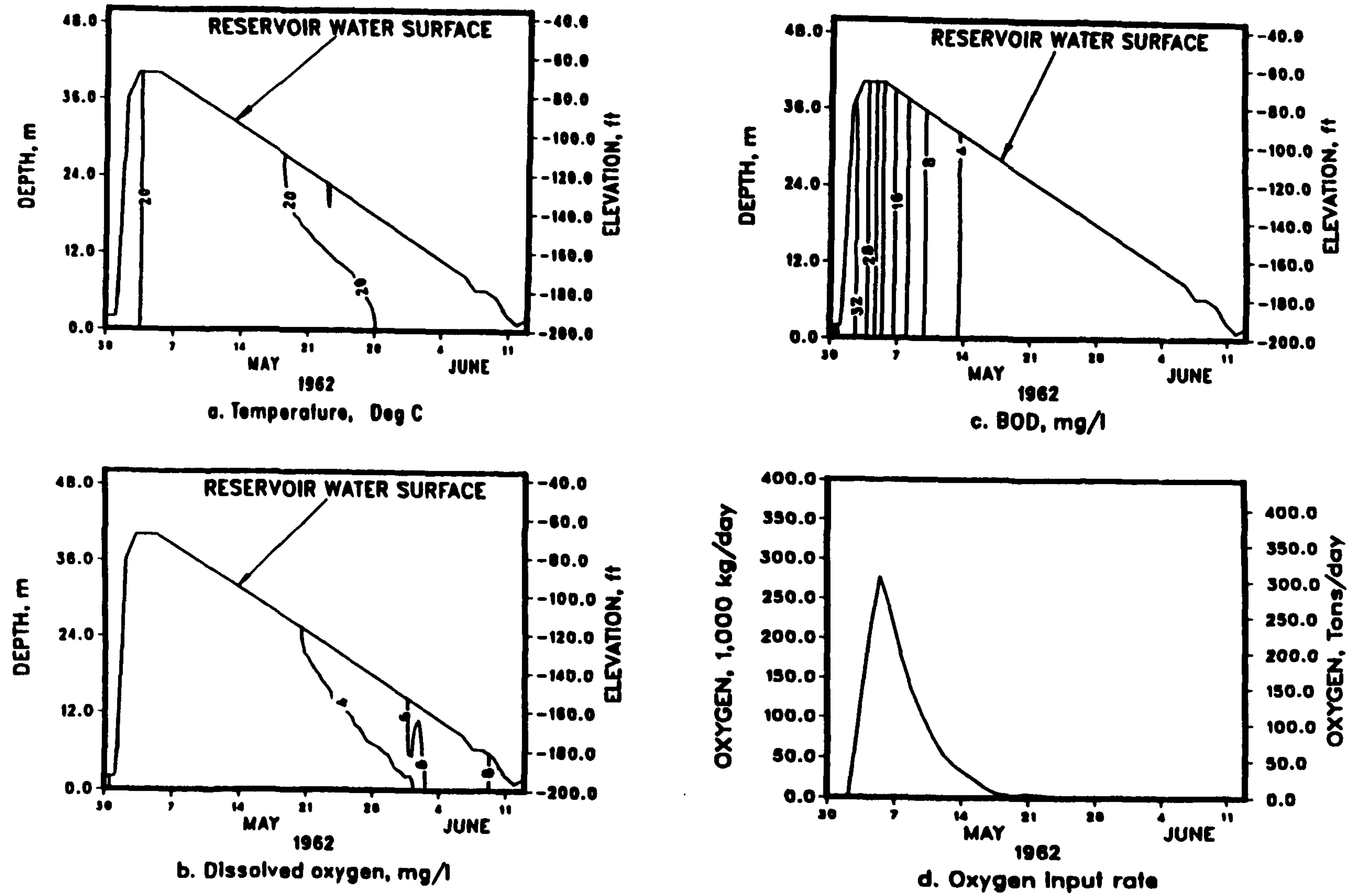


Figure 10. Temperature, DO, and BOD isoplots and required oxygenation rate for spring 1962 meteorological conditions

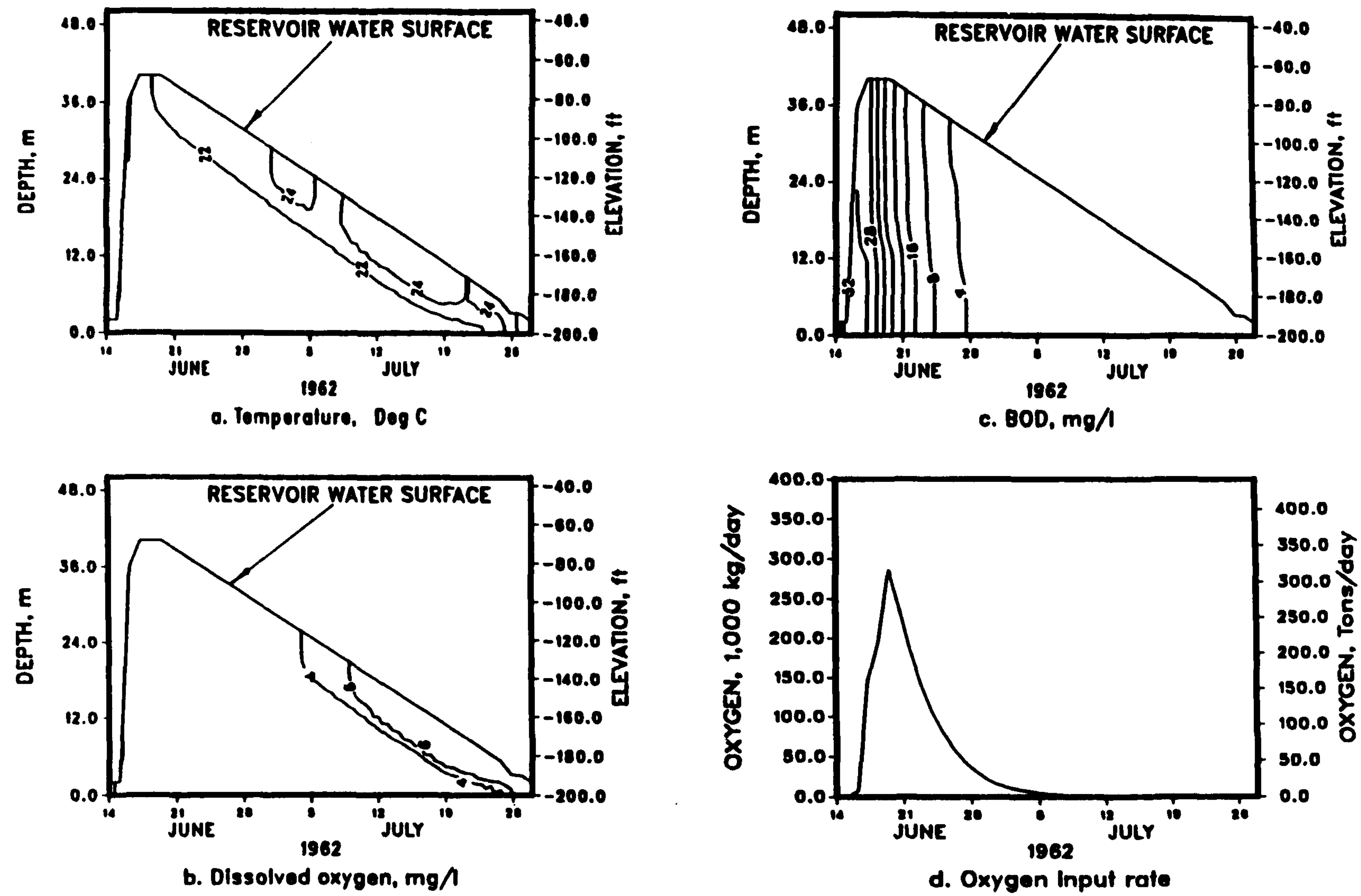


Figure 11. Temperature, DO, and BOD isoplots and required oxygenation rate for summer 1962 meteorological conditions

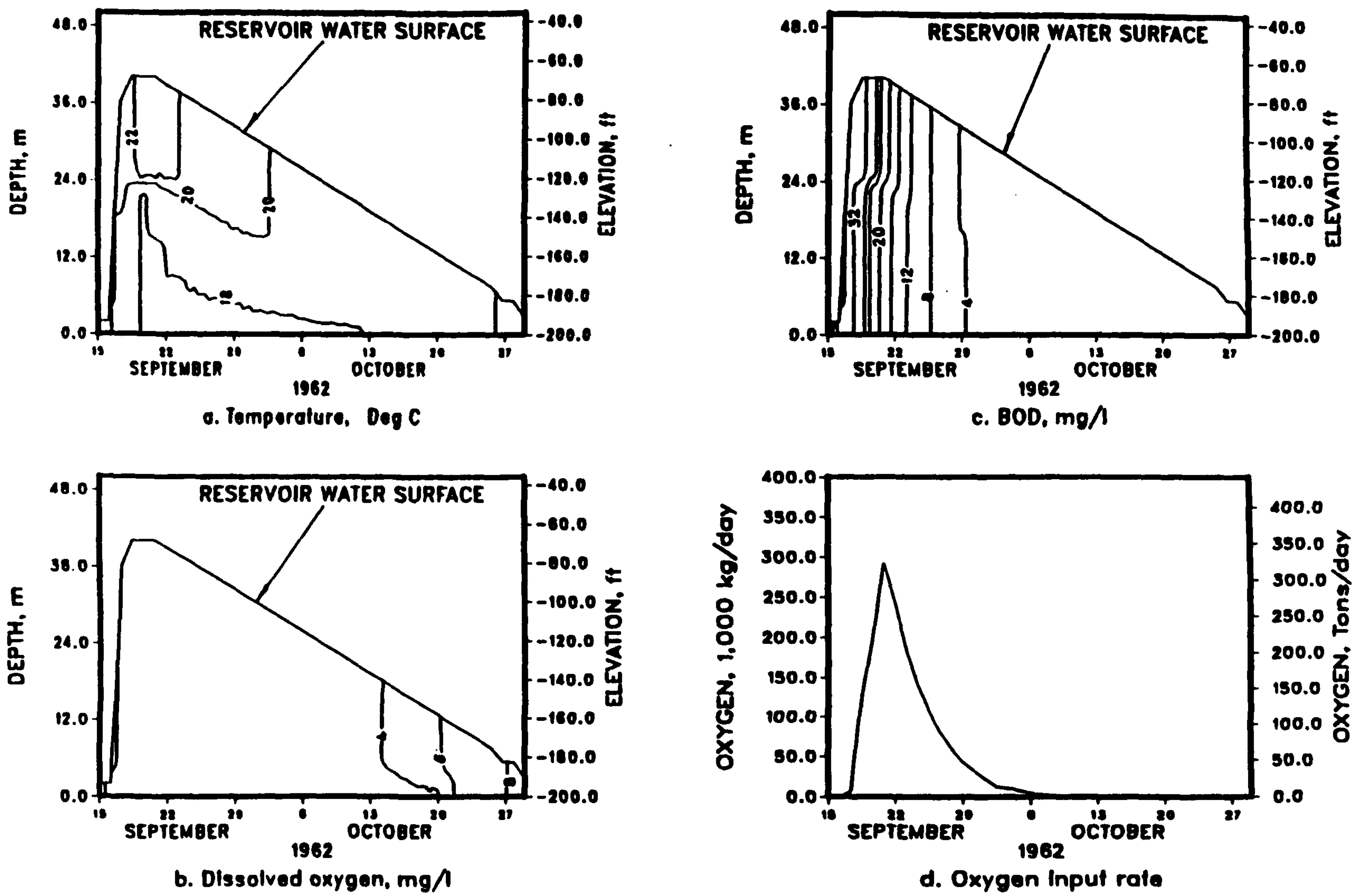
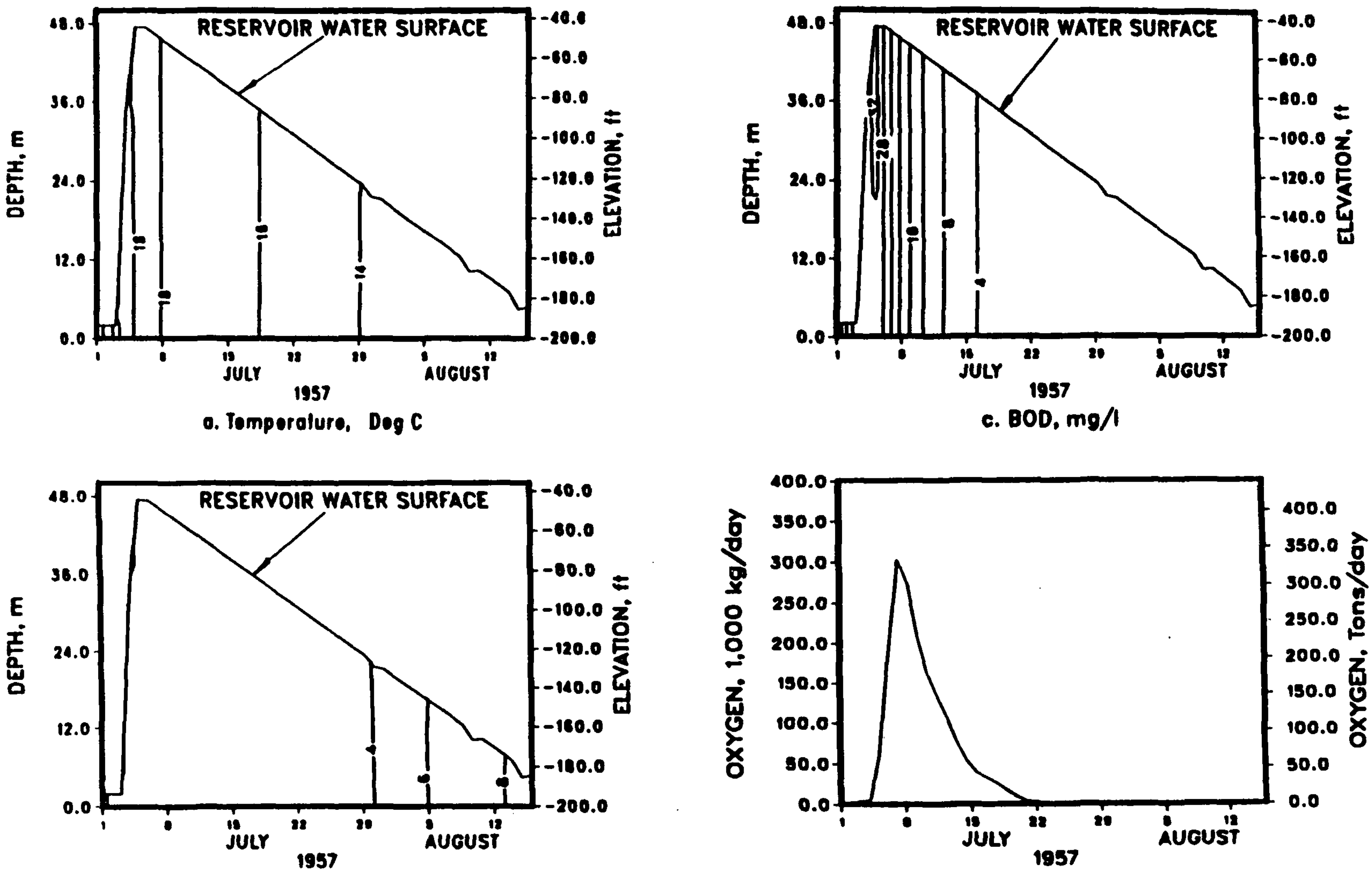


Figure 12. Temperature, DO, and BOD isoplots and required oxygenation rate for fall 1962 meteorological conditions



a. Temperature, Deg C

b. Dissolved oxygen, mg/l

c. BOD, mg/l

d. Oxygen input rate

Figure 13. Temperature, DO, and BOD isoplots and required oxygenation rate for 1957 meteorological conditions

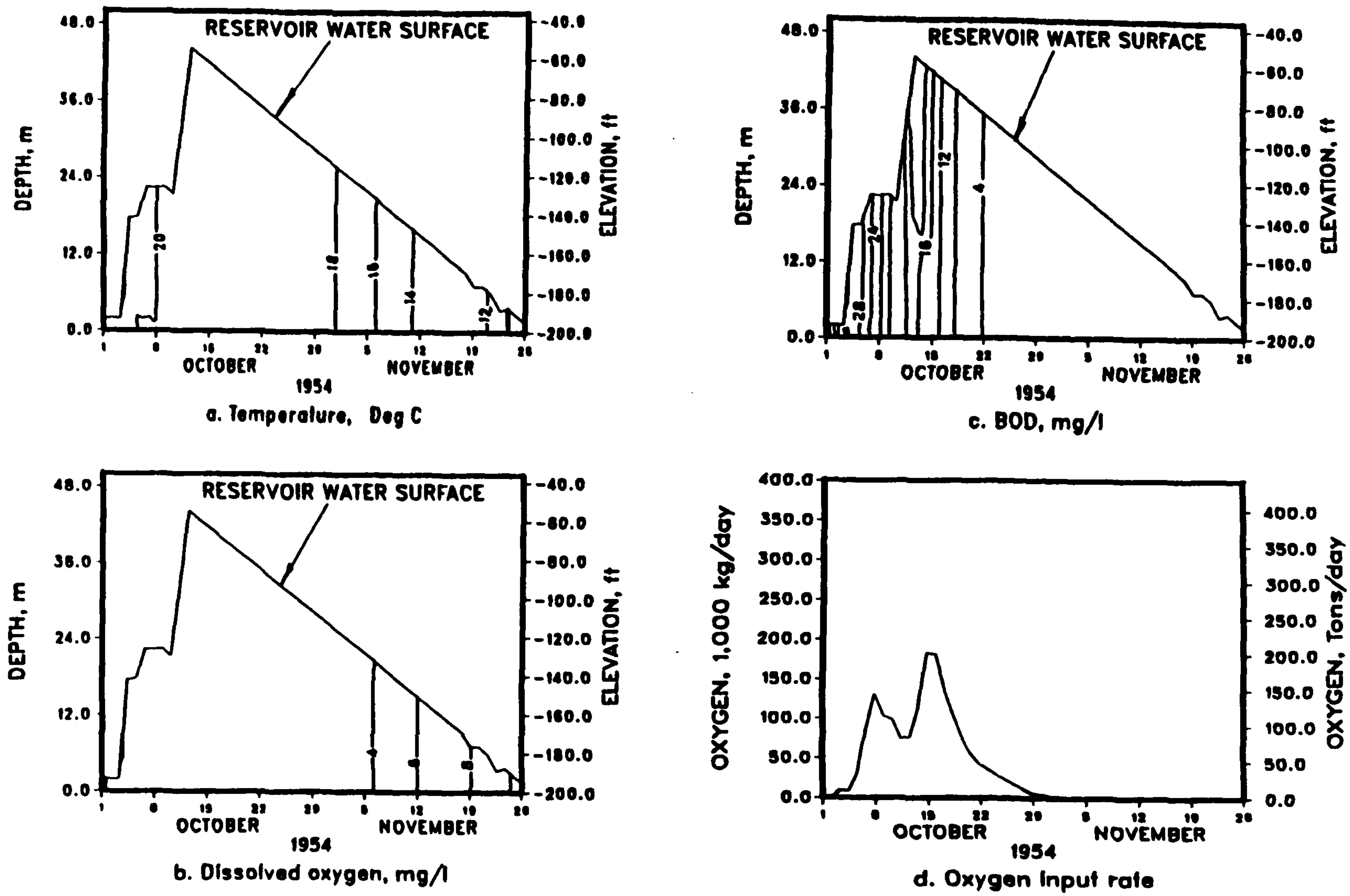


Figure 14. Temperature, DO, and BOD isoplots and required oxygenation rate for 1954 meteorological conditions

concentrations as high as for previous simulations, probably due to the delay in filling that allowed some assimilation to occur before the reservoir was filled. The predicted oxygen input rate was considerably less than for previous simulations, peaking at approximately 220 tons/day (200 metric tons/day).

41. Simulation of the 1954 flood indicated that partial filling may significantly reduce the required oxygen input rate as compared to the 10-year flood simulation. To investigate the effects of partial filling with other meteorological conditions, the average meteorological conditions (1949) were used with a modified inflow scenario. The reservoir was allowed to fill partially and be drawn down, then partially filled and again drawn down. This scenario (Figure 15) indicated thermal stratification would develop on the smaller pools and result in some DO stratification. Although BOD patterns for both drawdown sequences were similar, the required input DO rate was somewhat less for the second inflow, even though the total volume of water to be aerated in the reservoir was greater. This was probably due to dilution of the inflow since the pool was approximately 30 ft deep when the second storm inflow occurred. In both cases, the required maximum oxygen input rate was approximately 150 tons/day (136 metric tons/day).

42. The simulation of the effects of a destratification system on the reservoir were examined using the summer 1949 meteorological conditions, for which the thermal stratification was the strongest, and the 10-year flood event. The destratification system consisted of a single linear diffuser located on the reservoir bottom with an air flow rate of 1.2 m^3/sec. This air flow rate was estimated from field tests of destratification systems sized according to the reservoir surface area (Zic and Stefan 1990). No reaeration is assumed through the rising bubble column generated by the destratification system; but with movement of low-DO bottom water to the surface, increased surface reaeration may be sufficient to reduce the total amount of oxygen required to maintain aerobic conditions. Results of this simulation (Figure 16) indicated that destratification of the reservoir was possible (as indicated by the vertical slope of the temperature contours), but little impact was observed on the BOD and the required DO input rate when compared to the same simulation without the destratification system (Figure 5). The total amount of required oxygen was reduced by only 1.7 tons (1,520 kg) (0.08 percent of the total oxygen required). From these results, one would conclude that destratification had a minor impact on the required oxygen input rate.

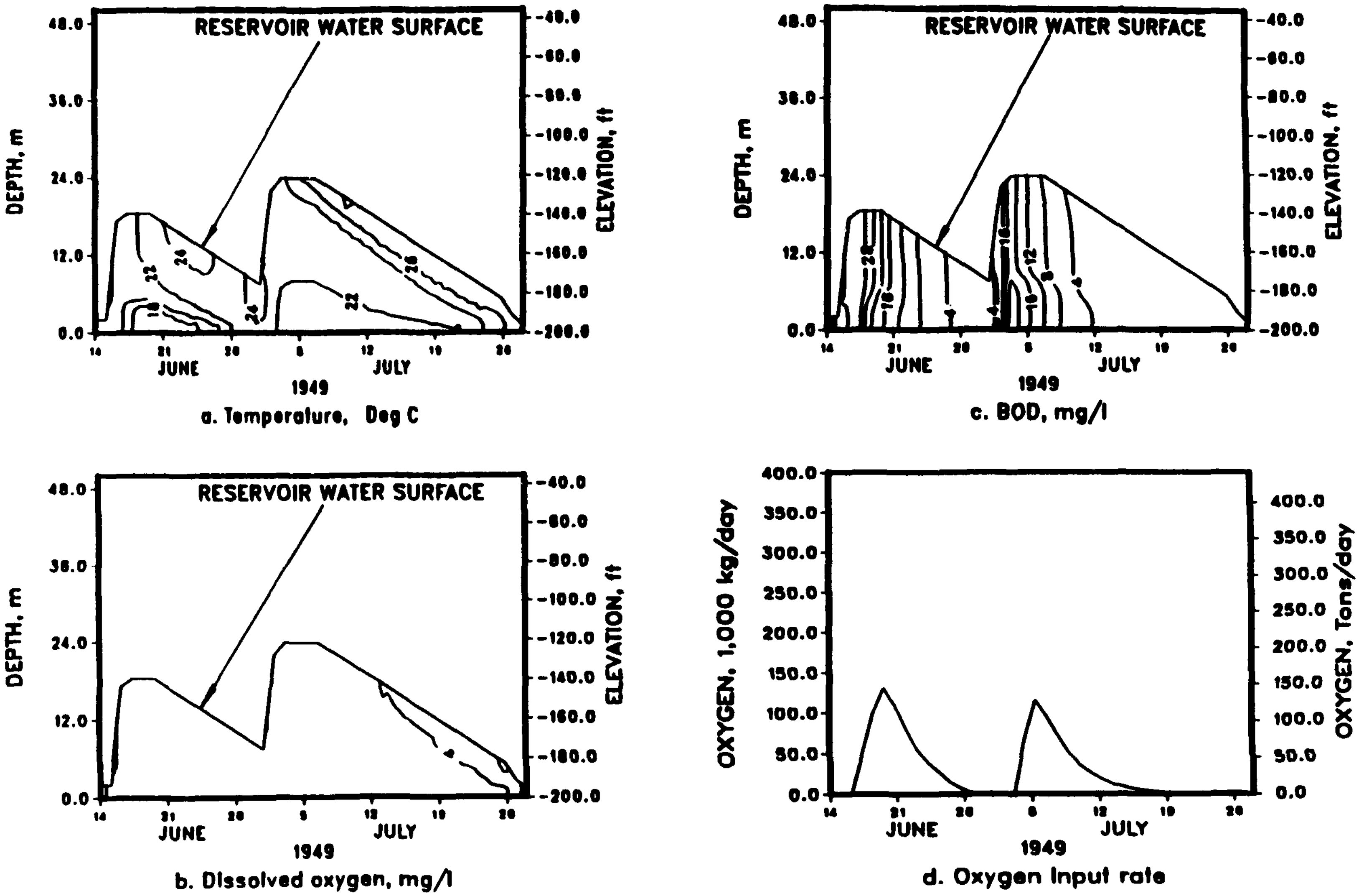
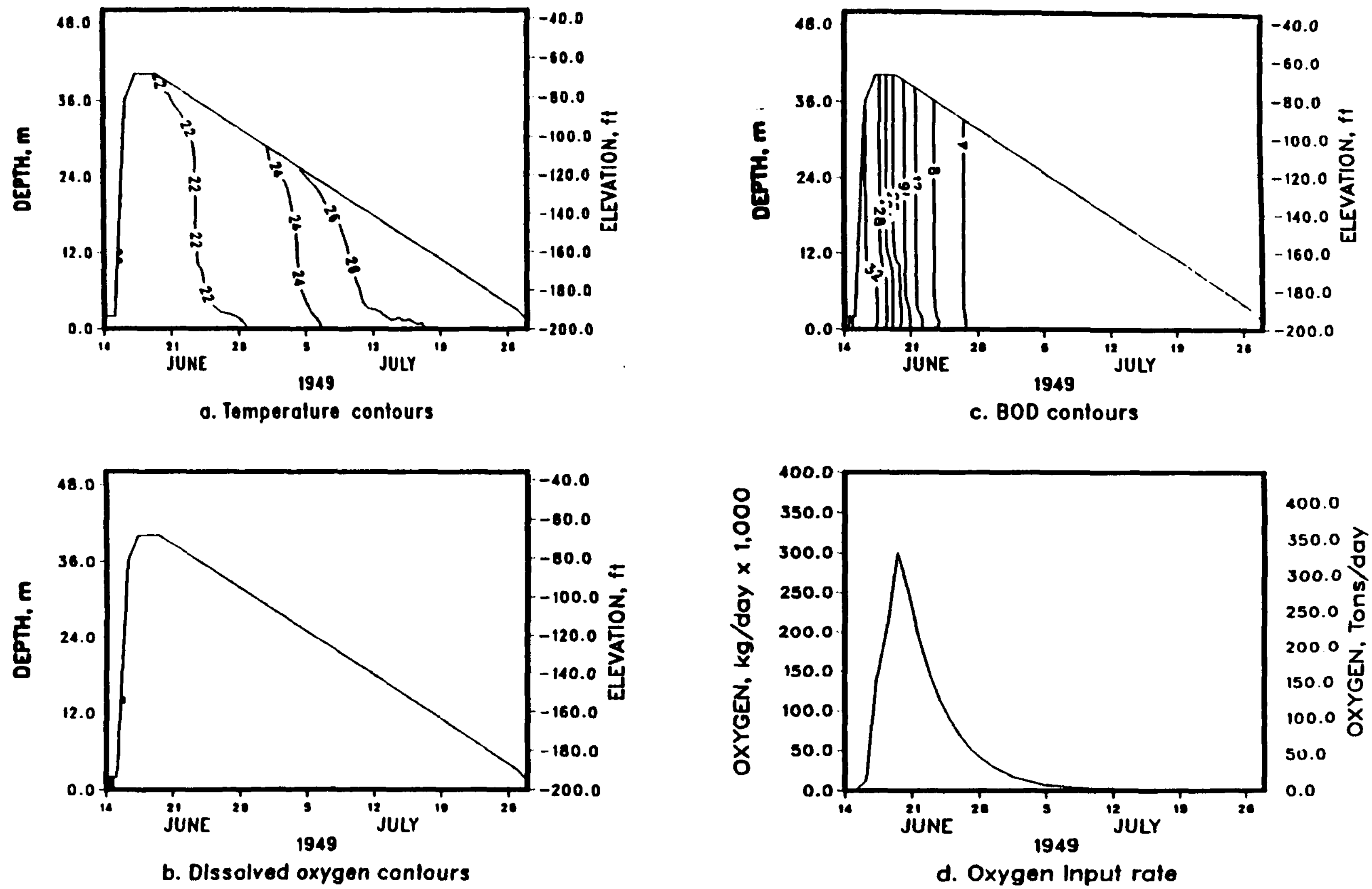


Figure 15. Temperature, DO, and BOD isoplots and required oxygenation rate for partial fill scenario



a. Temperature contours

b. Dissolved oxygen contours

c. BOD contours

d. Oxygen input rate

Figure 16. Temperature, DO, and BOD isoplots and required oxygenation rate for destratification scenario

However, the oxygen absorption from the rising bubble plume of the destratification system was not included in the simulation. Although not presently quantifiable, it is doubtful that a pneumatic destratification system could supply the required oxygen input. As a single system, destratification will not provide the needed reaeration for a fully mixed aerobic environment.

Evaluation of Facultative Pond and Fully Mixed Approach

43. The third objective of this investigation was to conduct simulations of the various scenarios to evaluate the two alternatives to prevent the escape of hydrogen sulfide. The fully mixed approach would require evaluation of the strength of stratification to determine the amount of energy required to maintain mixed conditions. The facultative pond approach relies on thermal and chemical stratification to maintain an aerobic layer on the reservoir. This layer prevents escape of hydrogen sulfide by oxidation. If an instability occurred in the water column, such as an inflow of warm water from the tunnel or passage of a weather front, vertical mixing could result in destratification, depletion of DO in the aerobic layer, and the subsequent release of hydrogen sulfide to the atmosphere. If model simulations indicate stratification is weak or does not develop, maintenance of a stable aerobic layer on the reservoir surface would be difficult. In this case, the fully mixed approach would be recommended. If stratification is predicted in most simulations, the facultative approach could be recommended.

44. Simulations of spring inflow scenarios for all 10-year inflow events indicated that thermal stratification was virtually absent. DO stratification developed with the 1982 spring simulation and to a lesser extent the 1962 spring simulation. Therefore, development of thermal stratification necessary for effective facultative operation was not predicted. Thermal stratification, when it did develop, was initiated usually within a few days after the reservoir was filled. The simulation of the summer scenarios indicated the development of thermal stratification with the strongest developing with a surface-to-bottom temperature difference of over 8° C in the 1949 simulation. The 1982 summer simulation indicated a weaker stratification with the 1962 summer stratification being very weak, with a top to bottom temperature difference of less than 4° C. The simulation of the fall scenarios indicated thermal stratification patterns similar to the spring simulations. The 1954

and 1957 simulations indicated little thermal stratification. Since development of stratification necessary for a facultative pond was not predicted for most simulations, implementation of this alternative would in all probability result in release of hydrogen sulfide. Therefore, the fully mixed approach, which requires aeration of the entire reservoir to maintain aerobic conditions, would be recommended for inflows of the 10-year-flood magnitude.

Dissolved Oxygen Requirements for Aerobic Conditions

45. The fourth objective of this investigation was to predict the amount of oxygen required to maintain aerobic conditions for each scenario. Using the oxygen addition routine described in paragraph 29, the simulations were conducted with the minimum oxygen set at 2.0 mg/ℓ. Results are shown in Figures 4-16. For all simulations except the 1954 scenario, the amount of oxygen required to maintain 2 mg/ℓ in the reservoir peaked at approximately 350 tons/day (318 metric tons/day). The peak demand followed the inflow in that as the pool filled and the BOD exerted its demand, the required oxygenation capacity increased. Once the BOD was satisfied, the required oxygenation capacity declined rapidly. The 1954 scenario was significantly different from the others in that the required oxygenation capacity was much less, on the order of 220 tons/day (200 metric tons/day). This was due to the partial filling allowing some assimilation of the BOD to occur before complete filling of the reservoir. Based on these simulations, an aeration system to maintain 2.0 mg/ℓ minimum DO in the reservoir should have a capacity to transfer 350 tons of oxygen per day (318 metric tons/day). Although this system capacity will be needed only for a few days, the aeration system must be capable of delivering oxygen at this rate to maintain aerobic conditions.

Numerical Model Sensitivity Analysis

46. The simulations were used to evaluate the effects of the various meteorological conditions on reservoir water quality with the same inflow water quality conditions. The number of inflow conditions that could be simulated are numerous and could require considerable time and effort to conduct. Rather than simulate all possible permutations of inflow and meteorological conditions, sensitivity analysis was conducted on selected input variables to

identify those with the greatest impact on the reservoir DO. The selected input variables were those most likely to influence the DO. Using the 1949 summer meteorological conditions with the 10-year flood event, inflow DO, BOD, temperature, sulfide concentration, surface mixing coefficient, and destratification system size were varied; and the effects on the total oxygen required to maintain 2 mg/ℓ for the entire storm event were observed. Values for each input variable spanned the range of values possible for the McCook Reservoir. For example, the inflow DO for the 1949 summer meteorological conditions was set to 3 mg/ℓ, instead of 6 mg/ℓ. The amount of oxygen required to maintain 2 mg/ℓ in the reservoir for the 45-day simulation was summed and compared to simulations with inflow DO of 0.0 mg/ℓ and 6.0 mg/ℓ (normal condition). Only one input variable was modified for each simulation and other input variables remained at their normal or default conditions as with previous simulations.

47. Results of this analysis are shown in Figure 17. The inflow oxygen concentration (ranging from 0.0 to 6.0 mg/ℓ) had a minor impact on the total oxygen required with more oxygen required for lower inflow DO concentrations.

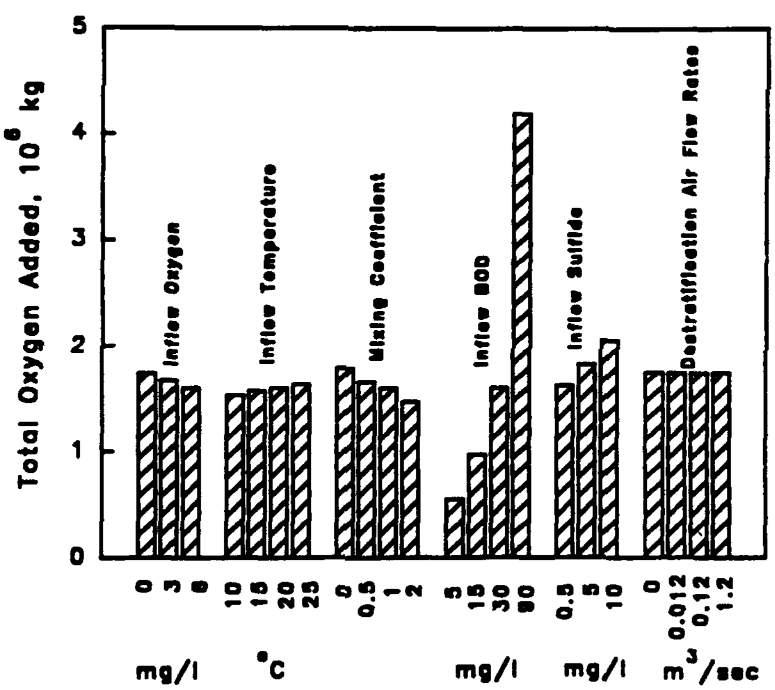


Figure 17. Total volume of oxygen required for various inflow parameters

A similar effect was observed with variation of the mixing coefficient (ranging from 0 to 2) with more oxygen required with lower mixing coefficients. Inflow temperature (ranging from 10° C to 25° C) also had a minimal impact with lower temperatures requiring less total oxygen to maintain 2 mg/ℓ. Inflow sulfide concentration (ranging from 0.5 mg/ℓ to 10 mg/ℓ) had a minor impact with increased sulfide concentration requiring more total oxygen. The variation in the air flow to the destratification systems (ranging from 0.012 m^3/sec to 1.2 m^3/sec) had the least impact on total oxygen requirements of the variables examined. The inflow BOD (ranging from 5 to 90 mg/ℓ) had the most significant impact with considerable variability in total oxygen requirements. Since the DO predictions in the model are heavily dependent on BOD, the model prediction of the total oxygen requirements is extremely sensitive to variation in inflow BOD concentration.

PART V: McCOOK RESERVOIR AERATION SYSTEM

Aeration System Design Criteria

48. The final objective of this investigation was to provide criteria for the design of an aeration system for the McCook Reservoir. This system design was based on the simulations of the required oxygen input to maintain 2 mg/ℓ DO in the reservoir for various meteorological conditions with a 10-year flood event. For storm events greater than a 10-year flood or inflow BOD concentrations greater than 30 mg/ℓ, simulations should be conducted to determine the required oxygen input rate and total amount of oxygen. This may result in a larger system than that discussed here.

49. The sizing of hypolimnetic oxygen injection systems for the Richard B. Russell Reservoir on the Savannah River in Georgia, as well as the system designed for Table Rock Reservoir on the White River in Arkansas, were based on the maximum single-day oxygen requirement. The maximum McCook oxygen input rate for most simulations as discussed in paragraph 45 was approximately 350 tons/day (318 metric tons/day). This rate is the amount of oxygen that must be dissolved in solution to meet the 2 mg/ℓ criteria for maintenance of aerobic conditions. Design of an aeration system must consider the oxygen transfer efficiency of the diffuser selected for installation as part of the design process. Oxygen transfer efficiency is defined as

$$OTE = \frac{O_2(\text{absorbed})}{O_2(\text{injected})} \tag{11}$$

where

OTE = oxygen transfer efficiency

O_2 (absorbed) = mass of oxygen absorbed by the water

O_2 (injected) = mass of oxygen injected by the aeration system

Manufacturers of diffusers supply OTE information specific to gas flow rate and depth. The depths at which most test information is developed are between 10 and 30 ft (3.0 and 9.1 m, respectively). The McCook Reservoir will fill to a depth of approximately 150 ft (45.7 m) and then be drawn down to a depth of less than 10 ft (3 m). The effect of the depth of the diffuser in this type of fluctuating environment can have a significant impact on diffuser OTE.

Diffuser Depth

50. Investigations conducted over relatively shallow depths have indicated that increased depth increases OTE ("Aeration" by Water Pollution Control Federation and American Society of Civil Engineers 1988). Tests in reservoirs with depths up to 150 ft (45.7 m) support this increase in OTE with depth (Schmit, Wren, and Redman 1978; Speece et al. 1976; Nicholas and Ruane 1975; and Mauldin*). Results of tests conducted by various investigators are shown in Figure 18. Although there is a degree of variability for diffusers at a given depth, the variability is probably due to such parameters as variation in bubble size (coarse versus fine) and water quality (oxygen uptake rate, temperature, etc.) of the test site, among others. To account for the effects of depth, a regression equation was developed for the points corresponding to the lowest efficiency for each depth. The equation is

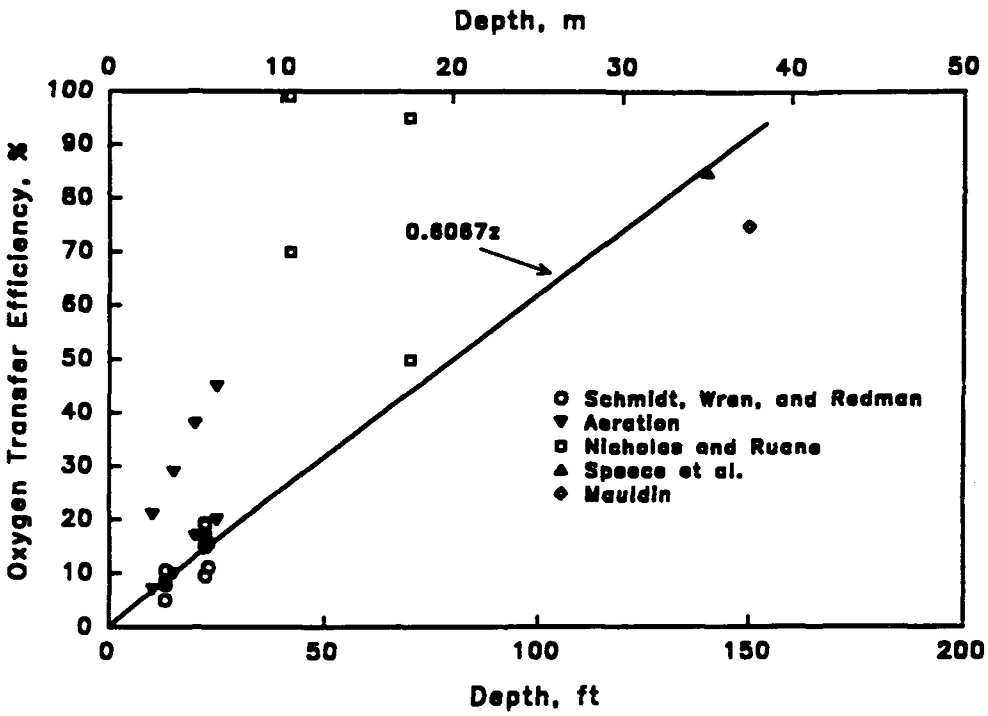


Figure 18. OTE for various diffusers at various depths

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* Personal Communication, 17 February 1989, from G. Mauldin, US Army Engineer Division, South Atlantic, Atlanta, GA.

$$OTE = 0.6067\ z \tag{12}$$

where

z = depth of diffuser, ft

Using this equation, the OTE for a diffuser system may be determined from the depth of the diffuser. For the McCook Reservoir, the OTE would vary from 4 percent at shallow depths to approximately 80 percent at full pool (Figure 19). Using this estimate of OTE, the amount of oxygen required to

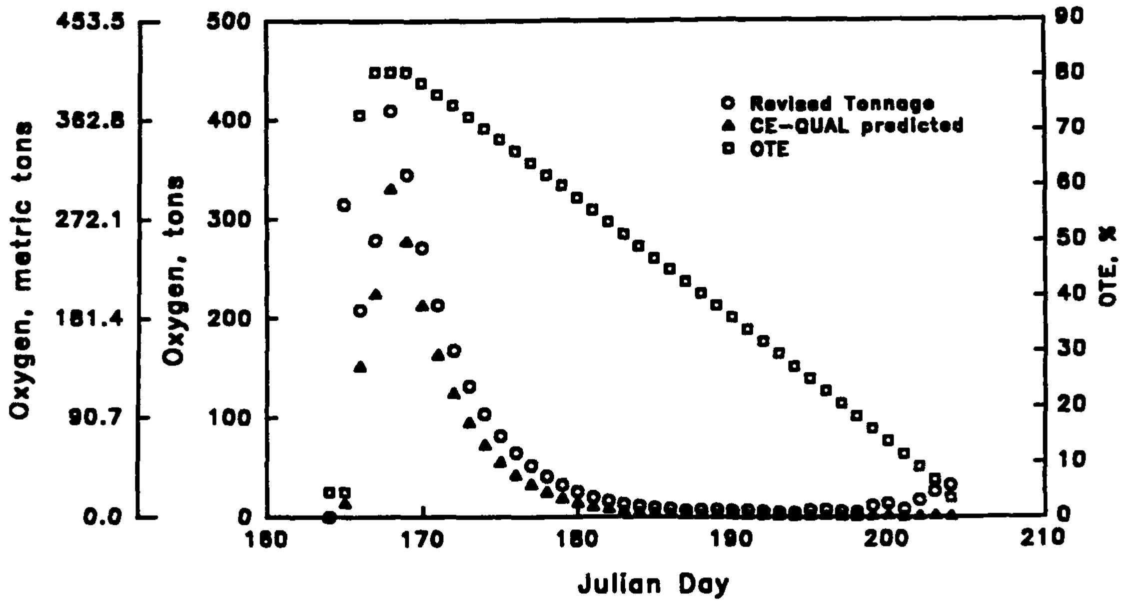

Figure 19. Model-predicted oxygen input rate, revised input rate, and OTE for summer 1949 meteorological conditions

maintain 2 mg/ℓ can be revised to reflect the OTE of a system using the following equation:

$$O_r = \frac{O_p}{0.01 * OTE} \tag{13}$$

where

O_r = revised oxygen input rate, tons/day

O_p = model-predicted oxygen input rate, tons/day

The input rate as simulated with the model along with the revised estimate of oxygen accounting for variation of OTE with depth are shown in Figure 19 for the 1949 summer meteorological conditions. Low OTE values due to shallow depths prior to filling and near the end of the simulation require

considerably more oxygen to maintain the aerobic conditions. In addition, during the peak demand, approximately 450 tons/day (408 metric tons) of oxygen, an increase of approximately 100 tons/day (91 metric tons) over previous simulations, are required to maintain aerobic conditions.

Diffuser Density and Placement

51. The number of diffuser heads required to deliver the oxygen to the reservoir depends on the diffuser head size and gas flow rate. Most diffusers have a range of gas flow rates at which OTE varies only slightly. For example, a 9-in.(23-cm)-diam flexible head diffuser produced by Wilfley Weber, Inc., is reported* to operate at gas flow rates of 0.5 scfm** (14.2 ℓ/m) to 6.5 scfm (184.0 ℓ/m) while a 13-in.(33-cm)-diam flexible head is reported to operate from 4 to 13 scfm (113 to 368 ℓ/m). The oxygen system installed at Richard B. Russell uses 7-in. (17.8-cm) ceramic diffuser heads, with a gas flow rate of 1.4 scfm (39.6 ℓ/m). The number of diffuser heads for a given oxygen input rate and diffuser gas flow rate can be determined from the following equation:

$$N = O_r * \frac{C}{Q_g} \tag{14}$$

where

N = number of diffuser heads

C = conversion factor from tons/day to scfm, 16.4151

Q_g = gas flow rate per diffuser, scfm

For the McCook Reservoir with a maximum oxygen delivery rate of 450 tons/day (409 metric tons/day), 5,276 diffuser heads would be required with a gas flow rate of 1.4 scfm (39.6 ℓ/m) per diffuser (7-in.-diam. ceramic diffuser).

52. Diffuser placement in wastewater treatment facilities has been investigated for effects on OTE. Most investigations indicate that full floor coverage or uniform distribution over the floor of the facility has the highest efficiency (Water Pollution Control Federation and American Society of

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* S. E. Howington and E. B. Meyer. 1990 (12 Jun). "Improving Dissolved Oxygen in the Releases from Table Rock Dam," Memorandum for Record, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

** SCFM is standard cubic feet per minute.

Civil Engineers 1988). Since the reservoir walls are nearly vertical, the reservoir bottom would be approximately 218 acres (88 hectares). Placement of 5,276 diffusers as used in the example in a full floor coverage arrangement would require installation of diffusers on 42.4-ft (12.9-m) centers. This would require approximately 43 miles (69.2 km) of piping, not including supply lines to the diffuser system. Other diffuser placement designs using single linear arrangement along a side or middle of a facility were reported to be less efficient (Schmit, Wren, and Redman 1978) but may have advantages by reducing system piping and mechanical systems. Therefore, loss of OTE with alternative diffuser placement should be considered relative to system costs. If changes in the McCook Reservoir operating depth or inflow water quality should occur, additional simulations should be conducted to determine aeration system capacity. A system to meet the revised operating condition can then be designed using Equations 12, 13, and 14.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

53. This investigation consisted of the following components: review of appropriate aeration techniques, modification of the CE-QUAL-R1 water quality model to predict dissolved oxygen from biochemical oxygen demand (BOD) loading to the McCook Reservoir, simulation of several potential reservoir operational scenarios, including destratification and sensitivity analysis, prediction of the required oxygenation capacity to maintain an aerobic reservoir for those scenarios, and a conceptual aeration system design.

54. Results of simulations indicated a facultative pond approach to prevent the escape of hydrogen sulfide may be difficult to operate due to weak thermal stratification. A fully mixed reservoir approach consisting of an aeration system with sufficient mixing should maintain aerobic conditions and should prevent the formation of hydrogen sulfide in the reservoir. Simulations of pneumatic destratification indicated that destratification alone will not maintain aerobic conditions in the reservoir. Sensitivity analysis indicated inflow BOD concentrations had the greatest impact on required oxygen input rates. Based on a review of aeration techniques, a bottom diffuser system is recommended for the McCook Reservoir. Based on the limited design information, preliminary aeration system design was provided that used 5,276 ceramic 7-in.(17.8-cm)-diam diffuser heads. The number of other types of diffuser heads may also be computed using the procedure described in paragraphs 48-52.

55. For final design and operational purposes, the aeration system design criteria require additional research. The estimate for oxygen transfer efficiency (OTE) used in the preliminary design in the previous section is a gross estimate of OTE. Pilot tests of the diffusers proposed for installation at McCook Reservoir should be conducted to determine OTE under conditions similar to those of the McCook Reservoir. Once the transfer efficiency is confirmed, the spacing and locations of the diffusers can be established. This could be accomplished by testing in a laboratory setting and then in an existing reservoir environment. A more detailed gas transfer model should be developed that would include the relationship between bubble size, air flow rate, and transfer efficiency.

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